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Alternative Electrical Energy Systems - A Comparison of the Risks of Occupational and Public Fatalities

by the

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on Nuclear Safety

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Alternative Electrical Energy Systems - A Comparison of the Risks of Occupational and Public Fatalities

ABSTRACT

A critical review is made of recent evaluations of the risks of fatalities, occupational and public, from three systems for the production of electricity: coal, nuclear, and hydraulic. It is concluded that the occupational risks of the coal fuel cycle are about 2 to 4 times higher than those from the nuclear or hydraulic systems, and that the public risks from the coal-fired system are also somewhat greater than those from the nuclear or hydraulic systems.

RÉSUMÉ

Le présent rapport fait l'examen critique des récentes évaluations des risques de mortalité pour les travailleurs et la population, imputable aux trois systèmes de production d'électricité : le charbon, le nucléaire et l'hydro-électricité. Il conclut, d'une part, que les risques pour les travailleurs du cycle du charbon sont d'environ deux à quatre fois supérieurs à ceux pour les travailleurs des systèmes nucléaire ou hydro-électrique et, d'autre part, que les risques du système au charbon sont aussi légèrement plus élevés pour la population que ceux qui viennent des systèmes nucléaire ou hydro-électrique.

Ce document est aussi disponible en français.

EXECUTIVE SUMMARY

ACNS-10

ALTERNATIVE ELECTRICAL ENERGY SYSTEMS - A COMPARISON OF THE RISKS OF OCCUPATIONAL AND PUBLIC FATALITIES

EXECUTIVE SUMMARY

INTRODUCTION

Forecasts indicate that electrical energy demand in Canada in the year 2000 will be about 50 per cent greater than in 1985. The growth in demand will be met primarily by large units (300 MW or more) of hydraulic, coal and nuclear generation.

The occupational and public health risks of different electrical energy production systems have been the subject of many studies in recent years. The Advisory Committee on Nuclear Safety decided that an evaluation of these studies would be useful in judging the risks of nuclear-electric energy in the broader context of the risks of electrical energy from other sources.

This report concentrates on the comparative risks of large coal, nuclear and hydraulic plants. Brief summaries of risk estimates for oil-and gas-fired electric power plants are appended. The report deals mainly with the risks of fatalities, whether by accident or disease, arising from normal operation but includes a discussion of the risks of catastrophic accidents.

There are very large differences in the risks estimated by various studies, for various reasons, e.g.;

- considerable variation in scope;
- uncertain relationships between exposure and effects;
- poorly understood chemical and physical behaviour of pollutants;
- inclusion or not of hypothetical severe accidents;
- various measures of harm.

A literature search was conducted for objective critical evaluations of recent risk studies of electrical energy systems. Only three such recent critical studies were found: those of Cohen and Pritchard [1], Paskievici [2], and Black and Niehaus [3]. Since the bases of the critical surveys of Paskievici and of Niehaus are reasonably comparable these surveys are used as the basis of this report, with reference to Cohen and Pritchard where appropriate.

None of these three studies consider the risks of hydraulic generation of electrical energy. Therefore, the recent studies of Inhaber [4] and Holdren [5] were used as the basis of the estimates of hydraulic risks.

As the above studies use data from different countries, this report first describes and summarizes these "world" data, and then describes risk estimates for the Canadian situation.

COAL FUEL CYCLE

Occupational Risks

For the coal fuel cycle, occupational fatalities from diseases are concentrated in the mining phase, resulting mainly from pneumoconiosis which may develop into fatal massive fibrosis. The high ends of the ranges of estimates of fatal diseases in the literature reflect older working conditions; new standards are expected to decrease fatality rates considerably. Occupational fatalities from accidents in the coal fuel cycle also occur mainly in the mining stage, although there is a significant hazard in the transportation phase, mainly from railway accidents.

The best-estimate ranges given by Paskievici and Niehaus for the total occupational fatalities associated with electricity production from coal-fired power plants and their fuel cycles are:

Occupational Fatalities in the Coal Fuel Cycle per Gigawatt-year (GWa)

	Diseases	Accidents
Paskievici	0.01 - 0.5	0.93 - 2.1
Niehaus	0.10	1.08 - 1.18

Public Risks

The over-riding cause of estimated public fatalities from the coal fuel cycle is premature death resulting from respiratory impairment attributed to emissions of pollutants such as SO_2 and NO_x from the stacks of coal-fired power plants.

The estimates of public fatalities from the long-term chronic effects of these pollutants rely mainly on epidemiological studies which have uncertainties due to factors such as age distribution, smoking habits and income levels. A recent analysis by Hamilton [6], which assumes an SO_2 emission rate corresponding to 67 per cent sulfur removal*, indicates that the total premature deaths in the USA as a whole would be about 15 excess fatalities per gigawatt-year (GWa) with a 90 per cent confidence range of 0 to 77. These values are not inconsistent with the best-estimate ranges of Paskievici and of Niehaus.

Public fatalities from accidents associated with the coal cycle occur almost entirely because of accidents in the transport of coal by rail. The best-estimate ranges of Paskievici and Niehaus are in good agreement with each other.

Public Fatalities from the Coal Fuel Cycle
fatalities/GWa)

	Diseases	Accidents
Paskievici	0.3 - 30	0.67 - 1.5
Niehaus	3.2 - 22	0.57 - 1.38

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* Typical of state-of-the art scrubber technology

Canada

Based on data of coal production and occupational fatalities in coal mining in Canada the average occupational fatality rate is about 1.17 per GWa.

Ontario Hydro data for fatalities during construction in the 1970's lead to a fatality rate of about 0.056 fatalities/GWa. There were no occupational fatalities in the period 1970-79 from the operation of their coal-fired power plants.

No information on occupational fatalities in the transport of coal to power plants in Canada is available.

Although there have been no detailed studies made of public fatalities in Canada from diseases from the coal fuel cycle, a study covering Ontario and Québec in 1979 estimated about 4 to 5 fatalities/GWa from local effects of SO_2 emissions. This is within the lower range of Paskievici (0.3 to 30) and of Niehaus (3.2 to 22) and slightly higher than the recent best-estimate value of Hamilton for local effects in the eastern USA (about 3 excess fatalities/GWa).

NUCLEAR FUEL CYCLE

The major occupational and public risk from the nuclear fuel cycle is latent cancer fatality caused by exposure to ionizing radiation. For the purposes of this report, a risk value of 1.0×10^{-2} fatalities per person-Sievert is adopted*.

Occupational Risks

The major occupational risks from diseases occur from workers being exposed: in uranium mining to radon daughters, in power plant operation to activated material and fission products, and, where it is used, in reprocessing of fuel to fission products and actinides.

Occupational risks from accidents occur mostly in the mining stage. The fatalities per GWa from mining uranium are about on order of magnitude less than for coal primarily because of the much higher energy content per tonne of material mined for average uranium ores as compared to coal.

Occupational Fatalities in the Nuclear Fuel Cycle
(fatalities/GWa)

	Diseases	Accidents
Paskievici	0.13 - 0.30	0.13 - 0.30
Niehaus	0.42 - 0.49	0.17

Public Risks

The major public risk in the nuclear fuel cycle comes from exposure to radioactive emissions from the power plants and from uranium mine tailings.

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* The International Commission on Radiological Protection assumes a value of 1.25×10^{-2}/person-Sievert for fatalities and 0.4×10^{-2}/person-Sievert for significant genetic effects in the first two generations.

Public fatalities from accidents in the nuclear fuel cycle occur primarily in transportation of fuel, wastes and other materials. Because less material is transported than for the coal fuel cycle, the estimated accident fatality rates are significantly lower and are are much smaller than the risks attributed to disease.

Public Fatalities in the Nuclear Fuel Cycle
(fatalities/GWa)

	Diseases	Accidents
Paskievici	0.1 - 0.4	0.008 - 0.018
Niehaus	0.27 - 0.32	0.003 - 0.006

Canada

The assessment of the applicability of these risk estimates to the situation in Canada is more imperative for the nuclear fuel cycle than for the coal fuel cycle since the technology of nuclear power in Canada is quite different from that used in most other countries, while the coal fuel cycle technology used is essentially the same as that used elsewhere.

Occupational Risks

There is good data for occupational radiation exposures in Canada. The total occupational collective doses for 1984 for uranium miners were 33.3 person-sieverts external dose and 3850 person-WLM* from radon daughters and for nuclear fuel processors, 0.22 person-sieverts. From this, the occupational risks for diseases for the fuel supply stage of the nuclear fuel cycle in Canada in 1984 can be estimated as about 0.046 fatalities/GWa. This is slightly lower than the estimate, based on world data, of Paskievici (0.05 fatalities/GWa) and considerably lower than the range, also based on world data, of Niehaus (0.28 to 0.30 fatalities/GWa). Lower Canadian figures might be expected because of the absence of UF_6 conversion and fuel enrichment in the CANDU fuel cycle.

The occupational fatality rate from accidents from uranium mining and fuel processing is about 0.053 per GWa. This rate is less than the best estimate of Niehaus, (0.094 fatalities/GWa).

The risk of fatal accidents during construction of Ontario Hydro nuclear generating stations is about 0.039 fatalities per GWa. This risk is somewhat less than that given by Niehaus, (0.055 fatalities per GWa).

The occupational exposures from the operation of nuclear power plants in Canada give an estimated risk of fatal cancers of about 0.048 to 0.058 per GWa. This range of values is considerably smaller than the best estimate range of 0.13 to 0.18 fatalities/GWa given by Niehaus, and the best estimate value of 0.15 fatalities/GWa given by Paskievici.

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* WLM - Working Level Month - a measure of exposure to the radioactive decay products of radon, a gaseous radioactive decay product of radium, that is always associated with uranium.

There have been no fatalities to date resulting from accidents in the operation of nuclear generating stations in Canada. Assuming that any such fatalities would follow a Poisson distribution, an upper limit to the accident fatality rate (68% confidence) can be estimated as about 0.022 per GWa. This value is somewhat above the best-estimate value of Niehaus, based on world experience, of 0.014 per GWa.

Public Risks

Based on an estimate of the total radiation exposure of the public from uranium mining and refining, it is estimated that the total public risk from the fuel supply stage of the nuclear fuel cycle in Canada in 1978 would have been about 5.9×10^{-5} fatalities per GWa. This is significantly less than the lower limits of the ranges from the literature surveyed by Niehaus and by Paskievici. The reasons for the very low risk estimated for Canada compared to the risks estimated elsewhere are not clear.

The total collective dose to the public from the operation of all nuclear generating stations in Canada for the period 1972 to 1978 is estimated to be about 62 person-sieverts. Since the total electrical energy produced by these stations was about 14.8 GWa, the estimated public risk for this period was about 0.042 fatalities per GWa. This is considerably lower than the best estimate value of Niehaus (0.19). The estimates for more recent years are even lower than for earlier years.

It is not expected that collective dose equivalents from high-level waste management will be very significant [7], and therefore the resulting risks can be ignored as a contributor to the overall nuclear fuel cycle risk.

Decommissioning risks should not affect the total occupational and public risks of the nuclear fuel cycle in Canada to any significant extent.

Heavy Water Production

Heavy water (D_2O) is an essential material for CANDU power reactors. The D_2O production plants use large quantities of hydrogen sulfide (H_2S), a toxic gas.

In the four D_2O production plants in North America that have operated for any significant periods, there have been no occupational nor public fatalities in about 65 plant-years of operation to date. From this, the upper-limit estimate of public and occupational risk from normal operation at a heavy water production plant is about 10^{-3} fatalities/GWa. This is negligible compared to the other risks associated with the CANDU fuel cycle.

It is concluded that occupational and public fatality risks for nuclear power plants in Canada may be less than the best-estimate values of Paskievici and Niehaus. However, since our assessment of the risks of the CANDU nuclear fuel cycle has been limited in scope and depth the best-estimate ranges of Paskievici and of Niehaus are used for the nuclear fuel cycle risks in Canada.

HYDRO-ELECTRIC SYSTEM

There is an order-of-magnitude difference between the occupational risks of hydraulic generation estimated by Holdren et al, and by Inhaber.

Holdren	0.16 - 0.26 (fatalities/GWa)
Inhaber	1.47 - 2.69 (fatalities/GWa)

From the assessments of Inhaber and Holdren et al, the only significant public risks from hydraulic generation, other than hypothetical high-consequence risks of dam failures, arise from the transportation of materials.

Canada

Occupational Risks

The estimated risk for the construction of hydraulic generating plants in the Ontario Hydro system is currently 0.28 fatalities/GWa. This is considerably lower than the low end of the range given by Inhaber (0.83 fatalities/GWa) which was based on earlier data from Ontario Hydro. Assuming that the estimates based on Ontario Hydro experience are typical for Canadian utilities, a range of 0.28 to 0.83 fatalities/GWa for construction risks in Canadian hydro-electric generation is used.

Using risk factors given by Inhaber, the occupational risk from transportation associated with the construction and operation of hydraulic generating plants is estimated to be in the range of 0.01 to 0.03 fatalities/GWa. If the approach of Holdren is assumed, the range of occupational transportation risk expands to cover a range from 0.005 to 0.10 fatalities/GWa.

The occupational risk during the operation and maintenance of Ontario Hydro hydraulic plants is given as 0.024 fatalities/GWa. This risk is much below that given by Inhaber of 0.63 fatalities/GWa which was based on experience in France.

Examination of data from other Canadian utilities indicates that Ontario Hydro occupational safety experience is representative. Since construction risks dominate the occupational risks for hydraulic power plants in Canada, uncertainties in the other stages do not significantly affect the total risks.

Public Risks

It is assumed that the only significant non-catastrophic public risks from hydraulic generation in Canada arise from transportation of materials. Based on materials data from Ontario Hydro the upper end of the range is about a factor of three lower than the lower end of the range given by Holdren.

	Public Fatalities (fatalities/GWa)
Canada	0.005 - 0.012
Holdren	0.03 - 0.22

CATASTROPHIC ACCIDENTS

A catastrophic accident may be defined as any calamity, disaster or misfortune, usually sudden. Different organizations use different criteria to classify an event as catastrophic.

The approach used for the assessment of the risks from catastrophic accidents in this report is primarily qualitative and descriptive. Major accidents that have occurred are reviewed to provide information on the total fatalities caused, both public and occupational. Then, from those probabilistic risk analyses (PRA) of hypothetical accidents which have been done, general conclusions are drawn.

Coal Fuel Cycle

Serious Accidents That Have Occurred

The only significant cause of catastrophic occupational fatalities in the coal fuel cycle is a serious mining accident. Both the frequency and magnitude of catastrophic mining accidents has decreased in recent years. Coal mining disasters in the USA often resulted in 200 to 300 fatalities or more per accident in the early part of this century but recent data indicate the average fatality rate per disaster was less than 20 over the period since 1951.

Accidents causing large numbers of public deaths that can be attributed to the coal fuel cycle include severe air-pollution episodes and collapses of mine waste piles.

Hypothetical Catastrophes

The only analysis found of hypothetical catastrophic accidents associated with the coal fuel cycle is a study cited by Cohen and Pritchard of serious accidents associated with the rail transport of coal in the UK. This considered collisions between passenger trains and trains carrying dangerous materials and led to an estimate of up to 600 deaths with a probability of 10^{-8}/year.

Assessment for Canada

Although catastrophes have occurred in underground coal mines in Canada, their frequency and the numbers of fatalities per accident have decreased in recent years. Moreover, most coal is now mined in open-pit mines. Thus, the present risk of catastrophic occupational accidents in the coal fuel cycle would be expected to be very low in Canada.

The collapse of coal-mine waste piles, explosions resulting from spontaneous combustion of coal-mine wastes or subsidence of abandoned coal-mine workings do not present any real risks of catastrophes in Canada, mainly because of present siting and environmental controls.

Nuclear Fuel Cycle

Serious Accidents That Have Occurred

There have been only two reactor accidents in which immediate fatalities have occurred, the SL-1 accident in the USA in 1960, in which two plant workers were killed by blast, and the Chernobyl-4 accident in the USSR in 1986, in which 31 plant and emergency workers were killed. However, there have been a few reactor accidents that have led to fuel damage and/or the release of some radioactivity to the building or to the environment.

The Soviet report on the Chernobyl-4 accident indicates that about 75 million people in the European part of the USSR may have been exposed to radiation from Chernobyl-4 and that the total collective dose commitment for the next 50 years to this population is 290,000 person-sieverts. This results in an estimated risk of about 2900 additional cancer deaths in this population (compared to about 10 million from other causes).

Hypothetical Catastrophes

Probabilistic risk assessment (PRA) has been applied to hypothetical catastrophic accidents in nuclear power plants much more than either coal or hydraulic ones. The results of a PRA are often presented as risk curves for which the total risk can be determined by an appropriate integration. The Rasmussen study in the USA in the mid 1970s estimated the risk to be about 0.03 public fatalities per GWa, which is well below the ranges of total public risk for normal operation of the nuclear fuel cycle given by Paskievici (0.1 to 0.42) and Niehaus (0.27 to 0.33).

Assessment for Canada

There have been no power reactor accidents in Canada leading to any significant occupational exposures.

Although no probabilistic risk analysis has yet been completed for a CANDU reactor, one is now being undertaken by Ontario Hydro for the Darlington reactor. It is unlikely that the risks of hypothetical catastrophic accidents in a CANDU would be greater than those in a PWR or BWR, considering the conservative approaches to reactor safety used in Canada and taking into account certain mitigating factors in the CANDU design.

Based upon two different data evaluations, the public and occupational risks from catastrophic accidents in heavy water production plants are estimated to range from about 17.7×10^{-6}/GWa to an upper limit of about 10^{-3}/GWa, while the risks based on the analysis of hypothetical severe accident scenarios lie in the range of about 1.6×10^{-6} to 4.3×10^{-5} fatalities/GWa. Since these estimated risk figures are so low, the risk from catastrophic accidents in heavy water plants can be ignored in the evaluation of the total risks of catastrophic accidents in the CANDU nuclear fuel cycle.

Hydro-electric System

Serious Accidents That Have Occurred

The most obvious catastrophic accidents associated with hydro-electric power generation are failures of dams resulting in severe flooding and many deaths. A number of such dam failures have occured causing hundreds or even thousands of fatalities.

Hypothetical Catastrophes

Studies undertaken in California estimated public fatalities from 34,000 up to as high as 260,000 from catastrophic failures of concrete hydro-electric dams. It is generally accepted that the frequency of a concrete dam disaster is of the order of magnitude of 10^{-4} per dam-year. Applying the frequency value to these California dams results in an estimated public risk ranging from 3 to 26 fatalities per year.

Assessment for Canada

No catastrophic failures of hydro-electric (or other) dams have occurred in Canada, nor have any analyses of hypothetical catastrophic failures of hydro-electric dams corresponding to PRA's for nuclear reactors been made in Canada.

CONCLUSION

Normal Operation

The occupational risks in the coal fuel cycle are about two to four times higher than the occupational risks in the nuclear fuel cycle, which are, in turn, about the same as those for hydro-electric generation.

The risks to the public from normal operation of the coal fuel cycle may be roughly an order of magnitude greater than those from the nuclear fuel cycle, which are in turn somewhat greater than those from hydraulic generation. There is, however, considerable uncertainty in the health effects of air pollution caused by coal-burning.

Catastrophic Accidents

The infrequent occurrence of catastrophic accidents precludes any quantitative estimates of the risks of such accidents based on experience.

Because probabilistic risk analyses of hypothetical catastrophic accident sequences have not been carried out on coal or hydro energy systems to the same extent as for nuclear energy systems, meaningful quantitative comparisons are not yet possible.

Catastrophic accidents associated with the energy systems considered here have not occurred in Canada, nor have any PRA studies of catastrophic accidents yet been completed for Canadian conditions. Nevertheless, it is unlikely that the risks of occupational and public fatalities from catastrophic accidents are significantly different for the Canadian energy systems than those considered in the studies referenced.

Comparative Risks

It is difficult to make an unequivocal comparison of the risks of occupational and public fatalities amongst the different electrical energy systems studied. For normal operation, the data indicate that occupational risks in the coal fuel cycle are significantly higher (2 to 4 times) than those in the nuclear and hydraulic systems. The results also suggest that coal-fired (and oil-fired) systems present greater risks to the public than do nuclear and hydraulic systems.

The risks of public and occupational fatalities from catastrophic accidents are very low for all the technologies assessed in this report, and furthermore are probably lower in Canada than in the world at large. The risks of fatalities from catastrophic accidents in CANDU systems appear to be lower than those in the LWR systems.

This assessment places the risks of nuclear generation of electricity into perspective with those of the feasible alternatives for the near future. The results also help to assure that the first qualitative safety goal proposed by the Advisory Committee on Nuclear Safety in an earlier report, "Safety Objectives for Nuclear Activities in Canada", that, "Nuclear activities should not lead to unacceptable risks to the workers involved or to the general public", is being achieved.

APPENDIX

Oil

The total occupational fatalities for the oil fuel cycle are about the same as those for the nuclear-fuel cycle and for hydraulic generation and are considerably less than those for the coal fuel cycle. The total public fatalities for the oil fuel cycle are comparable to the high estimated values for the coal fuel cycle, again because of air pollution from combustion, and are thus an order of magnitude higher than the estimated total public fatalities from the nuclear fuel cycle and from hydraulic generation.

Gas

The total occupational fatalities for the gas fuel cycle are slightly less than those for the nuclear fuel cycle and for hydraulic generation and thus are considerably less than those for the coal fuel cycle. The total public fatalities for the gas fuel cycle are comparable to those for nuclear power and above those for hydraulic generation.

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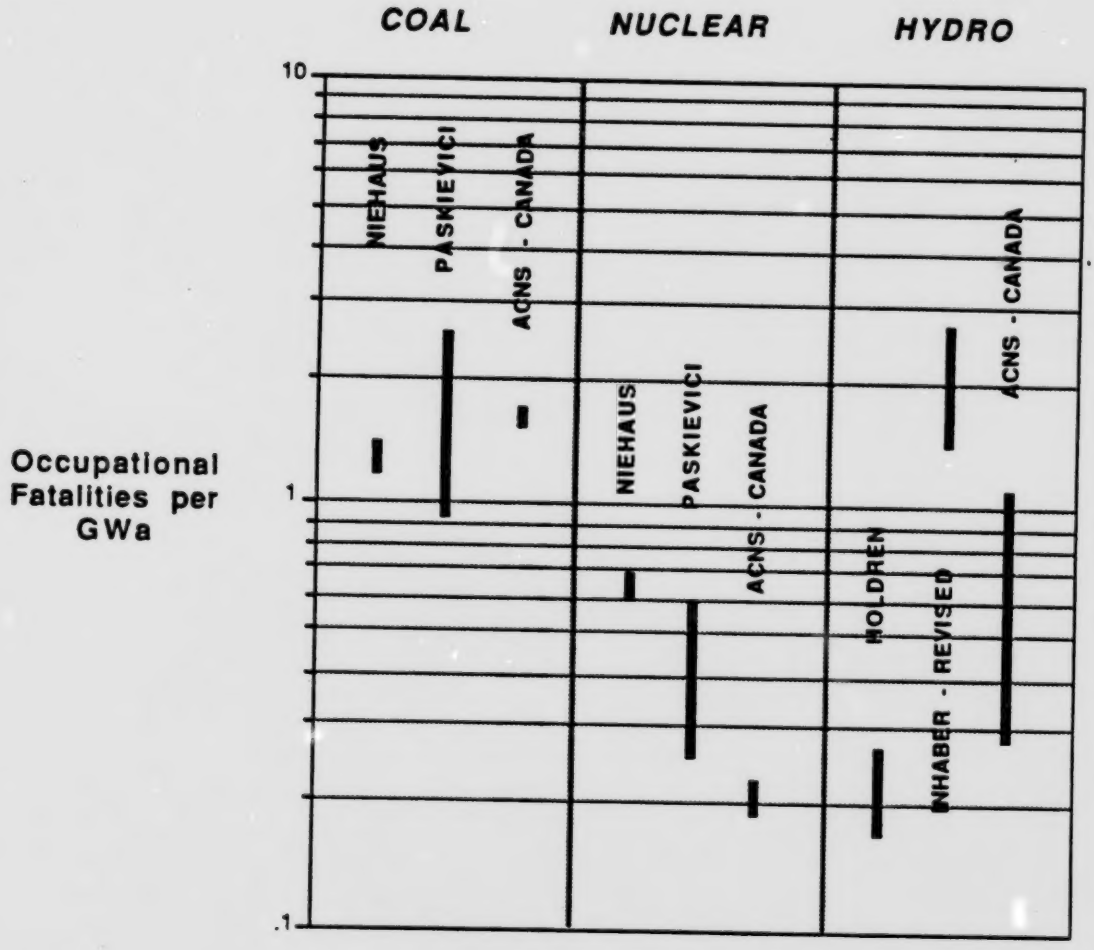
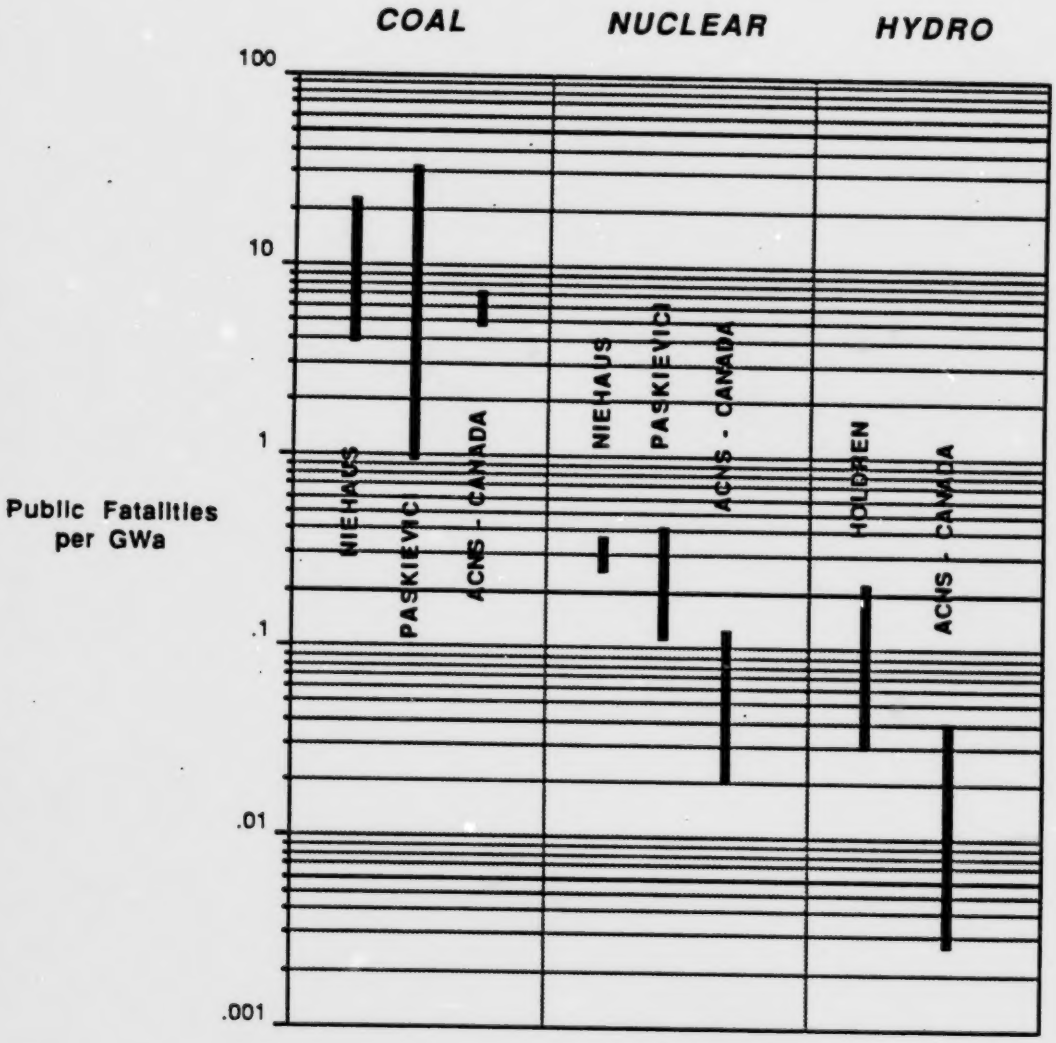


Risks of occupational fatalities from electrical energy systems



Risks of public fatalities from electrical energy systems

ALTERNATIVE ELECTRICAL ENERGY SYSTEMS - A COMPARISON OF THE RISKS OF OCCUPATIONAL AND PUBLIC FATALITIES

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ALTERNATIVE ELECTRICAL ENERGY SYSTEMS - A COMPARISON OF THE RISKS OF OCCUPATIONAL AND PUBLIC FATALITIES

1. INTRODUCTION

Many studies have been undertaken in recent years on occupational and public health risks of different electrical energy production systems. It is the view of the Advisory Committee on Nuclear Safety that a summary of recent critical evaluations of these studies would be useful to the Atomic Energy Control Board as well as to the Advisory Committee itself to aid them in seeing the risks of nuclear-electric energy in the broader context of the risks of electrical energy from other sources.

Forecasts of electrical energy demand in Canada to the year 2000 show continuing growth, with demand in 2000 being about 50% greater than in 1985 [1].

This growth in demand will be met mainly by large generating units, with capacities of 300 Megawatts (MW) and larger [1]. Therefore, this report considers the occupational and public health risks of such generating units.

In 1984, about 425 Terawatt-hours (TWh) of electrical energy were produced in Canada, which constituted about 42% of the total primary energy production [1]. Almost all of this electrical energy was produced in five main types of power plants. These types are listed below, together with the electrical energy produced in each in Canada in 1984 [1].

Hydraulic	285 TWh
Coal	77 TWh
Nuclear	51 TWh
Oil	9 TWh
Gas	4 TWh

The proportions of electrical energy generated from these sources in the future in Canada will not remain as above. In particular, little, if any growth can be expected in electrical generation from oil and gas-fired plants.

Thus, the growth in demand will be met by increases in hydraulic, coal and nuclear generation [1,2]. No significant contributions to electrical generation from other sources can be expected for at least the next quarter century [2]. Therefore, this report concentrates on the comparative risks of coal, nuclear and hydraulic plants and these are discussed and evaluated in the body of the text. Brief summaries of risk estimates for oil- and gas-fired electric power plants are given in Appendices 1 and 2.

While a major concern lies with public health effects, occupational risks associated with the different means of electric energy production must not be ignored and are covered in this report. The report considers the risks of fatalities, public and occupational, resulting from the use of each technology.[1] Furthermore, these fatalities are sub-divided into those resulting from accidents and those from diseases. In all cases, the estimated detriments are normalized to one gigawatt-year of electrical energy production. The production of electricity contributes to the increase of wealth of society, which, among other benefits, increases resources available for public health. Thus, the normalization of detriments to gigawatt-years provides an indication of cost-benefit ratios for the various systems considered. The report deals mainly with the risks of fatalities, whether by accident or disease, arising from normal operation. However, a discussion of the risks of catastrophic accidents in the various energy systems is also provided.

Non-fatal detriments are not considered in this report, but there is a rough proportionality between non-fatal detriments and fatalities, in most cases (e.g. 6). Adverse environmental effects and the costs of foregone use of land resulting from both normal operation and catastrophic accidents in electric power systems are also not considered here.

2. DIFFICULTIES IN EVALUATION OF HEALTH HAZARDS OF ENERGY SYSTEMS

As mentioned earlier, many studies have been undertaken of the health hazards of electrical energy systems. The results of these studies often show very large differences in the estimated hazards of particular systems.

There are many reasons for such discrepancies, the most important of which are summarized below:

a) Boundary Conditions

The scope of different risk studies can vary considerably. Some consider the hazards associated with the fuel cycle only (sometimes only part of the fuel cycle), while others include hazards of construction of the power plants. Others include the risks of the production of the materials used in construction (e.g. 3,4), which are important for materials-intensive technologies like hydraulic power and other systems based on renewable or continuous sources.

Assumptions as to the apportionment of risks of certain activities which have other end uses as well as contributing to a fuel cycle, such as coal-mining, may also lead to differences in risk estimates.

Some studies include the risks of distribution and end use of the generated electricity, while others do not. Differences also arise because of different space and/or time limits used in the estimates of harmful effects of substances released.

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[1] While the estimated reduction in life expectancy might be a more useful criterion, this information is not always available.

b) **Mechanisms of Harmful Effects**

While dose-response relationships are well accepted for certain hazards, e.g., radioactivity, there is considerably less acceptance of these relationships for other hazards, e.g., SO_2 or sulfates in the atmosphere. Moreover, dose-effect relationships are often established from relatively high doses or dose rates, so that even when these are reasonably well accepted, uncertainties arise on extrapolation to low dose rates, especially when threshold behavior may exist.

For some pollutants, e.g., SO_2, no mechanism for a possible or suspected biological effect from a pollutant has been clearly established. Thus, risks from such a pollutant are highly uncertain or speculative, even when epidemiological studies suggest that effects may exist. Additional difficulties arise with data from epidemiological studies because of confounding effects of age, income, lifestyle and other factors.

Another difficulty arises because of long periods between exposures and harmful effects for most pollutants at low concentrations.

Of course, even when mechanisms are known and correlations established, there are statistical variations within and between studies.

c) **Chemical and Physical Behavior of Pollutants in the Environment**

The chemical behavior of many pollutants in the environment is not well understood, e.g., sulfur oxides and sulfates. Also, dispersion and other aspects of physical behavior are often difficult to predict and are affected greatly by the meteorological and topographical assumptions used. Therefore, considerable uncertainties in predicted health effects can arise, depending on assumptions made about these parameters.

d) **Population Assumptions**

Predicted effects of pollutants are directly dependent on the total population assumed to be affected in the assessment models and the spatial distribution of this population.

e) **Established Versus New Technology**

Considerable differences in risk estimates can arise because of different assumptions about the inherent characteristics of the plant itself and in the emission control technology assumed to be applied.

f) **Inclusion of Hypothetical Accidents**

Some studies include risks arising only from accidents that have been observed, while others include estimates of risk for hypothetical low-probability accidents that have not been observed and which must therefore be speculative. The risks of low-probability, severe accidents are often included for nuclear power plants, but not generally for other types of power plants.

g) **Inclusion of Different Types of Harm**

While some studies differentiate clearly between fatalities from accidents, fatalities from chronic diseases, injuries and curable sickness, others do not, or may equate a fatality to a certain number of working days lost. Discrepancies in the results of studies can result from differing assumptions on these points.

Of course, differences can also occur because of errors in data and errors in interpretation.

Unfortunately, published studies do not always make clear which approaches or assumptions have been used. Others using the results of such studies may infer or assume a different basis from that which was actually used, thus confounding the results further.

3. RECENT CRITICAL EVALUATIONS OF THE LITERATURE

In view of these considerations, it was decided to search the literature for objective critical evaluations of recent risk studies of electrical energy systems, in an effort to establish comparative risks for the different systems on a consistent basis. Only three such recent critical studies were found: those of Cohen and Pritchard in 1980 [5], Paskievici in 1982 [6] and Black and Niehaus in 1980 [7]. The data summarized by Paskievici in reference 6 are mainly from his earlier critical reviews [8,9,10], and the results of Black and Niehaus are also summarized and up-dated in reference 11 (1982).

All three studies provide ranges from the literature for adverse health effects, broken down into occupational and public categories with each category divided into accidents and diseases for several different methods of electrical energy production. Each of these studies is restricted in certain ways, as discussed below.

Cohen and Pritchard [5] draw only qualitative conclusions on the comparative risks of different electricity production systems, so that the usefulness of their survey for the present purposes is somewhat limited.

Paskievici [6,8,9 & 10] recommends best-estimate values for each type of detriment from original studies for each system studied and provides uncertainty bands for these best estimates. The bases for the choices of these values are given as follows [9,12]:

a) risks associated with non-fuel resources are excluded. That is, risks associated with construction of the facilities and with the production of materials other than fuels are not considered.

b) use of present-day technology, including emission control technology, is assumed. That is, the estimated risks are those for new ("marginal") plants rather than the average plant in the system.

c) linear, non-threshold dose-effect relationships are assumed.

d) long-term risks (> 500 years) are ignored or discounted.

e) risks of large-scale hypothetical accidents are excluded. Thus, low-probability but high-consequence nuclear reactor accidents are not considered, nor are such accidents as large explosions at oil refineries.

f) distribution and end-use risks are excluded, being considered essentially the same for all alternatives.

While many uncertainties remain, these assumptions reduce the ranges of the estimates considerably.

Niehaus and colleagues [7,11] use an approach similar to that of Paskievici. They do not include the effects of hypothetical severe accidents, they exclude distribution and end-use risks, they consider state-of-the-art technology, they assume linear, non-threshold dose-effect relationships and ignore risks beyond 100 years [13]. Unlike Paskievici, they do, however, include risks from power plant construction but these are specified separately [7,13].

Thus it is concluded that the bases of the critical surveys of Paskievici and of Niehaus are reasonably comparable. The results of these surveys are used as the basis of this report, with data from Cohen and Pritchard being used where appropriate.

Unfortunately, neither Paskievici[2], Niehaus, nor Cohen and Pritchard consider the risks of hydraulic generation of electrical energy. There is very little information in the literature on risks from this technology, presumably because of its lack of importance for the future in most developed countries. The only recent studies identified were those of Inhaber [3] and Holdren [4]. Examination of these references shows that the main contributors to occupational risk are acquisition of materials and construction. For public risk, Holdren considers only transportation of materials while Inhaber considers only dam failures. Thus, these studies are not on the same basis as those of Paskievici and Niehaus, so that comparisons may be difficult. In addition, there are considerable differences between the results of Holdren and those of Inhaber. Nevertheless, in the absence of other recent studies, these two were used as the basis of the estimates of hydraulic risks for this report.

The studies used as the bases for this report depend on data gathered from many sources from different countries. Therefore, the estimated risks for a given energy source do not necessarily reflect those for the same energy source in Canada. In this report, we will first describe and summarize the data from "world" sources, and then discuss modifications that seem appropriate for the Canadian situation.

We now proceed to discuss coal-fired, nuclear and hydraulic plants in turn and to compare their risks.

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[2]In reference 8, Paskievici simply quotes the estimates of Inhaber [3] for risks of hydraulic generation.

4. RISKS OF FATALITIES FROM THE COAL FUEL CYCLE

Paskievici [6,8,9,10,12] reviewed the studies of the risks of coal-fired power plants and their fuel cycles given in references 14-30. Niehaus and colleagues [7,11] also reviewed the studies given in references 14, 18, 21 and 27 and, in addition, those of references 31-44. Cohen and Pritchard [5] also reviewed references 14, 15, 18, 21, 23, 25 and 28 and, in addition, the work of Black and Niehaus [7] as well as references 45-50.

4.1 Occupational Risks from the Coal Fuel Cycle

The ranges of estimates of total occupational fatalities associated with electricity production from coal-fired power plants and their fuel cycles from the literature reviews of Paskievici, Niehaus, and Cohen and Pritchard, and the best-estimate ranges of Paskievici and Niehaus, are given in Table 1.

The distribution of the occupational fatalities from accidents among the different stages of the coal fuel cycle is shown in Table 2, from the literature reviews of Paskievici, of Niehaus and of Cohen and Pritchard. Niehaus also gives best-estimate ranges for the distribution. No breakdown by stage is given for occupational fatalities from diseases since these all occur at the mining (fuel supply) stage.

4.1.1 Occupational Risks from Diseases

For the coal fuel cycle, occupational hazards from diseases are concentrated in the mining phase, resulting mainly from pneumoconiosis which may develop into fatal massive fibrosis. The high ends of the ranges of estimates of fatal diseases in the literature reflect older working conditions; new standards are expected to decrease fatality rates considerably, hence the relatively low best-estimate values selected by Paskievici and by Niehaus compared to the upper limits in the literature surveyed.

The ranges of fatality estimates from the different sources in the literature also reflect different working practices in various countries. For example, the values depend on the relative contributions of underground and open-pit mining to coal supplies. Niehaus based his estimates on US conditions where 55% of coal is produced in open-pit mines and 45% in underground mines [7].

The zero lower-limit fatality values, quoted by some American sources as shown in Table 1, are based on the assumption that medical check-ups would detect incipient pneumoconiosis, and the worker would then be removed from the mine.

In the judgement of Paskievici [9], the study undertaken by Morris, et al., [27] is the most comprehensive, and his selected values of mean fatality rate and its range reflect this judgement. Niehaus does not specify a range of values for fatalities but his selected mean value agrees exactly with that of Paskievici, 0.10 occupational fatalities from disease per Gigawatt-year (GWa), all from the mining stage (fuel supply).

Table 1

Occupational Fatalities in the Coal Fuel Cycle

(Fatalities/GWa)

Sources	Type of Fatality	Range from Literature Reviewed	Best Estimate Mean	Best Estimate Range
Paskievici	Diseases	0 - 8.7	0.10	0.01 - 0.5
	Accidents	0.19 - 7.5	1.4	0.93 - 2.1
Niehaus	Diseases	0.0008 - 6.4	0.10	---
	Accidents	0.54 - 6.2	--	1.08 - 1.18
Cohen and Pritchard	Diseases	0 - 9.3	--	---
	Accidents	0.53 - 8.0	--	---

4.1.2 **Occupational Risks from Accidents**

As for fatalities from diseases, occupational fatalities from accidents in the coal fuel cycle occur mainly in the fuel supply (mining) stage, although there is a significant hazard in the transportation phase also, as can be seen in Table 2, resulting mainly from railway accidents.

Again, as for fatalities from disease, the upper ends of the ranges of estimates of accident fatalities reflect past safety standards. Accident rates in coal mining have been falling rapidly in recent years [9]. Also, as for fatal diseases, the frequency of fatal accidents in coal mining depends on mine safety standards in different countries and such factors as the relative proportions of open-pit and underground mining.

The estimates of accident fatalities in the transport phase generally assume a certain average distance for rail transport of coal. Data for USA may be based on transport distances of 500 km and more [51] while data for Europe may be based on shorter distances (e.g. 50 km in the UK [5]). Niehaus [7] assumed US conditions for coal transportation, with an average transport distance of 500 km, and with fatalities based on 65% of coal transported by rail, 21% by truck and 13% by barge. An interpretation difficulty exists in some of the data in the literature for accident fatalities in the transportation phase since total fatalities have been cited, including public as well as occupational deaths. Paskievici has selected a mean value of occupational fatalities from accidents of 1.4 fatalities/GWa, with a range from about 0.93 to 2.1. Niehaus has selected a range of 1.08 to 1.18 fatalities/GWa from occupational accidents. The mean value in this range and the range itself are in good agreement with the values selected by Paskievici.

Table 2

Distribution Among the Stages of the Coal Fuel Cycle of Occupational Fatalities from Accidents

(Fatalities/GWa)

Stage	Source	Range From Literature Reviewed	Best Estimate Range
Fuel Supply	Niehaus	0.45 - 2.71	0.66 - 0.73
	Paskievici	0.19 - 2.30	--
	Cohen & Pritchard	0.44 - 2.84	--
Transport	Niehaus	0.073 - 3.07	0.35 - 0.38
	Paskievici	0.014 - 5.0	--
	Cohen & Pritchard	0.073 - 5.0	--
Plant Operation	Niehaus	0.013 - 0.46	0.016
	Paskievici	0.01 - 0.09	--
	Cohen & Pritchard	0.013 - 0.20	--
Construction	Niehaus	--	0.055
OVERALL	Niehaus	0.54 - 6.2	1.08 - 1.18
	Paskievici	0.19 - 7.5*	0.93 - 2.1
	Cohen & Pritchard	0.53 - 8.0	--

* Extremes of stage ranges are from different sources. Therefore, they do not sum to these values.

4.2 Public Risks from the Coal Fuel Cycle

The ranges of estimates from the literature for public fatalities associated with electricity production from coal-fired power plants and their fuel cycles, from the studies of Paskievici, Niehaus, and Cohen and Pritchard, and the best-estimate ranges of Paskievici and of Niehaus are given in Table 3.

Niehaus also gives a distribution by stage of the fuel cycle for public fatalities from diseases for coal-fired power plants, as summarized in Table 4.

4.2.1 **Public Risks from Diseases**

The single over-riding cause of public fatalities from the coal fuel cycle is premature death resulting from respiratory impairment attributed to emissions of pollutants from the stacks of coal-fired power plants during normal operation, as can be seen in Table 4. The major emissions of concern are particulate matter[3], SO_2 and NO_x.

Tables 3 and 4 show that there are very large ranges in the literature for premature public fatalities from diseases resulting from the coal fuel cycle. Much of these spreads results from different assumptions about emission controls used and about the sulfur content of the coal. However, even when these effects are allowed for, the ranges of the best estimates of the studies reviewed by Paskievici and of Niehaus (for modern power plants with state-of-the-art emission controls [12,13]) are still quite wide, as can be seen in Tables 3 and 4.

Table 3

Public Fatalities Resulting from the Coal Fuel Cycle

(Fatalities/GWa)

Source	Type of Fatality	Range From Literature Reviewed	Best Estimate Mean	Best Estimate Range
Paskievici	Disease	0 - 405.3	3.0	0.3 - 30
	Accidents	0.40 - 5.3	1.0	0.67 - 1.50
Niehaus	Disease	1.4 - 154	-	3.2 - 22
	Accidents	0.15 - 1.9	-	0.57 - 1.38
Cohen and Pritchard	Disease	0 - 167	-	-
	Accidents	0.40 - 2.53	-	-

[3] Particulate matter consists mainly of small particles of ash, carried out with the flue gases, which contain a variety of non-combustible substances, some slightly radioactive, including mercury and other heavy metals. Although coal-fired power plants are equipped with very efficient electrostatic precipitators (and bag-house filters in some cases) which should remove approximately 99% of particulate matter, the small fraction not removed contributes to air pollution.

Table 4

Distribution Among the Stages of the Coal Fuel Cycle of Public Fatalities from Diseases

Source: Niehaus

(Fatalities/GWa)

Stage	Range from Literature Reviewed	Best Estimate Range
Fuel Supply	1.3 - 14	--
Transport	--	--
Plant Operation	0.1 - 140	3.2 - 22
Construction	--	0.008 - 0.059
Total	1.4 - 154	3.21 - 22.1

The range widths of these best estimates can be attributed to a number of reasons. We are concerned here with long-term chronic effects of quite low concentrations of pollutants (<100 $\mu g/m^3$) on the population as a whole. While acute air-pollution incidents have occurred in the past [47,52-Table 6.1], causing many hundreds of premature deaths, it is very difficult to extrapolate from these acute incidents to low-level chronic effects for the following reasons:

a) The concentrations of pollutants in these cases were very much higher than those of concern here and exposures generally lasted for only a few days.

b) Almost all of the premature deaths in those cases occurred amongst old people with pre-existing respiratory diseases [47].

c) There are apparently synergistic effects caused by SO_2 and particulate matter occurring together at high levels which resulted in greater adverse health effects than caused by either occurring alone [47, 53].

Therefore, the estimates of public fatalities from diseases from the operation of coal-fired power plants rely mainly on certain epidemiological studies in the USA, supported by the observations of the acute effects at high levels of exposure and some evidence of effects of acute exposures in animals [5]. There are, however, uncertainties in the epidemiological studies because of confounding factors such as age distribution, smoking habits and income levels. There are also considerable uncertainties in the chemistry and physics of the pollutants in the atmosphere, as well as uncertainties in the biological mechanisms by which adverse health effects may occur.

Nevertheless, the detailed work of Hamilton and his colleagues at Brookhaven National Laboratory [47,51,54], as well as their re-evaluation of the work of other researchers, provides evidence of a correlation between sulfate concentration (used as a surrogate for fossil-fuel air pollutants in general) and pre-

mature death rates, although risk coefficients, i.e., excess deaths per 100,000 population per $\mu g/m^3$ of pollutants, vary from about 3.5 to 7.0 on an age-weighted basis [51].

Based on these BNL results, Hamilton and co-workers have estimated the number of excess public deaths per year from a 1000 MW coal-fired power plant in the vicinity of Pittsburgh, assuming a linear, no-threshold, dose-effect relationship [51]. The excess deaths were estimated for a region within 80 km of the plant with a population of three million. The plant was assumed to have a 305m stack height, to burn various types of coal and to have various levels of sulfur removal.[4]

Assuming that long-distance effects from such a plant would result in 10 times as many premature deaths in the USA as a whole than those within the 80 km radius, they conclude that a typical modern coal-fired plant meeting US Environmental Protection Agency emission standards, (burning low-sulfur coal with 90% sulfur removal from the flue gas), would result in a median value of 9.2 excess fatalities per GWa, with a 90% confidence range of 0 to 46. A more recent analysis of Hamilton [54], assumes that an SO_2 emission rate corresponding to 67% sulfur removal would be more realistic for the present. This analysis also included an improved model for long-range transport which indicates that the total premature deaths in the USA as a whole would be 5 times, rather than 10 times, those within 80 km of the plant. Combining these two modifications, Hamilton now estimates a median value of about 15 excess fatalities per GWa.

It should be recognized, however, that a number of authorities believe that the evidence for adverse health effects at mean annual concentrations of SO_2 and particulates below 100 $\mu g/m^3$ is very tenuous and that there may be a threshold in this range below which no adverse effects occur [5]. Hamilton acknowledges that expert opinion is quite divided on the magnitude and even the existence of adverse health effects from fossil-fuel power plant emissions [54]. For this reason, some studies have refrained from making numerical assessments of premature public deaths resulting from air pollution from coal-fired power plants (e.g., 4, 14, 23, 30) and Cohen and Pritchard state that such figures must be approached with extreme caution [5]. Also, McCarroll [55] has pointed out that stringent sulfur-emission controls in New York City since 1965 have reduced SO_2 concentrations by a factor of about 5 and SO_4 concentrations by a factor of about 2, without any effect being demonstrated on mortality figures.[5] Taking all evidence into account, Hamilton assigns a 90%-confidence range of 0 to 77 to his best-estimate value of 15 [54]. Considering the many uncertainties in such estimates, the results of Hamilton's recent analysis [54] are not inconsistent with the best-estimate ranges of Paskievici and of Niehaus as given in Table 3.

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[4] Niehaus assumed a population of 2.2 million within 80 km of the plant, ignored long-range effects, and assumed sulfur removal corresponding to 0.5% S coal and a 305m high stack [13]. For the dose-effect relationship [13], he estimated the lower bound from Lave [35,38] and the upper bound from model of Winkelstein [e.g., 51].

[5] It should be noted that particulate matter concentrations did not decrease during this period [53].

Thus, for our purposes, there is no need to modify the best-estimates of Paskievici and Niehaus, which are in adequate agreement with one another.

There is evidence that NO_x emissions from coal-fired power plants can also cause adverse health effects. Hamilton estimates upper limit effects of NO_x to be of the same order as the upper limit effects of sulfates [51]. However, in the epidemiological studies on which the present risk coefficients are based, sulfate concentration was used as the surrogate for air pollution in general, so that the risk coefficients include adverse effects of NO_x. Of course, most of the NO_x in the atmosphere comes from automobile exhausts [52] so that there is probably some upward distortion of the risk coefficients because of this factor.

There are no other significant sources of public fatalities from disease in the coal fuel cycle, since possible effects of stack emissions of radioactive materials from coal, and of pollutants from fires in coal storage piles are negligible compared to the estimated effects described above [5,6,7,9,10].

4.2.2 **Public Risks from Accidents**

Public fatalities from accidents associated with the coal cycle occur almost entirely because of accidents in the transport of coal by rail. The values from the literature given in Table 3 reflect information from different countries, in which the transport distances and rail system characteristics and practices may be quite different. Notwithstanding this fact, the best-estimates ranges of Paskievici and Niehaus are in good agreement with each other.

4.3 **Assessment of the Risks of Fatalities from the Coal Fuel Cycle in Canada**

The applicability of the foregoing risk estimates to the fuel cycle of coal-fired power plants in Canada is assessed in this section of the report.

Data on total occupational fatalities in coal mining in Canada are given by Paskievici [8] and Prossin [56]. The average total fatality rate per 100 man-years (production labor) for the years 1970 to 1975 from reference 8 was 0.178 and from reference 56 for 1970 to 1977 was 0.186[6]. We use the average value of 0.182 fatalities per 100 man-years. This total fatality rate includes accidents and diseases, as well as accidents going to and from work.

Data on coal-mining production in Canada for 1983, given by Romaniuk and Naidu [59], are summarized in Table 5. The occupational fatalities per GWa for the various types of coal mined can be estimated from the data in Table 6, assuming an average power plant efficiency of 35%. Results are summarized in Table 6, which shows that the weighted average total occupational fatality rate per GWa for coal mining in Canada is about 1.17. This value is above the best-estimate total values for coal-mining, 0.76 to 0.83, given by Niehaus (0.10 from Table 1

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[6] No breakdown between fatalities in underground and open-pit coal-mining is given. It should be noted that over 90% of the coal mined in Canada is surface mined and that the total fatality rate in open-pit mines is lower than in underground mines [53,57,58].

plus 0.66-0.73 from Table 2). The figure for Canada includes fatalities from accidents in travelling to and from work, which are not considered by Niehaus, so the two estimates may be in better agreement than the above figures indicate.

Table 5

Coal Production in Canada, 1983
Source: Romaniuk and Naidu [59]

	% Surface Mined	10^6 Tonnes Produced	Average Calorific Value, MJ/kg
Bituminous	83.9	22.5	29.8
Sub-bituminous	100	14.20	24.4
Lignite	100	7.5	17.0

Productivity:

Surface-mined - 7362 tonnes/man-year*
Underground-mined - 1356 tonnes/man-year*

* Production man-years for saleable coal only.

Table 6

Estimated Total Occupational Fatalities in Coal Mining in Canada in 1983

Assumed coal power plant efficiency - 35%
Fatalities/100 man-years - 0.182**

Coal Type	Percent of Total	Tonnes/ MWa	Man-years/ MWa	Fatalities/ GWa
Bituminous				
Surface	42.7	3024	0.411	0.75
Underground	8.2	3024	2.23	4.06
Sub-bituminous, surface	32.1	3692	0.501	0.91
Lignite, surface	17.0	5301	0.720	1.31

Weighted average fatalities per GWa = 1.17

** Production man-years only, average for 1970-1977.

Hamilton and Wilson [60] provide data on occupational fatalities during construction of Ontario Hydro fossil-fuelled power plants during the period 1970-1979. They report a total of five fatalities during the construction of three generating stations. One of these stations was an oil-fired station, at which no fatalities occurred during construction [61]. Thus, for the two coal-fired plants, with a total installed capacity of 5900 MW, assuming a capacity factor of 0.5 and a lifetime of 30 years, the calculated fatality rate is 0.056 fatalities/GWa. This rate is almost identical to that given by Niehaus in Table 2, 0.055 fatalities/GWa.

No information on occupational fatalities in the transport of coal to power plants in Canada is available. The fatality rate might be affected by the long transport distances for western coal burned in Ontario Hydro coal-fired stations but, on the other hand, U.S. coal burned by Ontario Hydro, the major fraction, is transported relatively short distances and partly by boat. In the absence of other data, we will accept the best-estimate range of figures of Niehaus, as given in Table 2.

Data from Ontario Hydro on the operation of their coal-fired power plants show no occupational fatalities for the period 1970-79 [60]. However, lacking information from other utilities, the best-estimate value of Niehaus may be accepted as being representative of the situation in Canada.

As far as we are aware, there have been no detailed studies made of public fatalities in Canada from diseases from the coal-fuel cycle. We might expect estimates of fatalities per GWa to be less than those of Hamilton [51,54] for the USA because of the lower population density in Canada. Rough estimates have been made by Hill [53] and by Simms et al [62], for coal-fired power plants in Canada. Lidstone [63] provides the results of a study of the local public health effects resulting from SO_2 emissions in Canada.

Using the Brookhaven [47] and the North and Merkover [18,53] analytical models, Lidstone estimates that the annual local public fatalities in Canada from SO_2 emissions in the late 1970's ranged between 160 and 200, of which between 141 and 178 occurred in Ontario and Quebec. These results may be used to estimate the local public fatality rate from SO_2 emissions from coal-fired power plants in central Canada.[7] Data for 1979 from reference 64 show that about 191 x 10^3 tons/year of SO_2 were emitted from fossil fuel power plants (mainly coal-fired) in central Canada, compared to about 1741 x 10^3 tons/year of SO_2 from other sources. The total electricity generated from fossil fuels (about 92% coal, estimated from reference 65) in Ontario in 1979 was 30,925 GWh [65] while in Quebec there was essentially none. There were no SO_2 emission controls in these plants. From these figures, public fatalities in Ontario and Quebec in 1979 from the <u>local</u> effects of SO_2 emissions from coal-fired power plants in this region can be estimated to be about 4 to 5 fatalities/GWa. These figures, which ignore

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[7] There would also be public fatalities in Canada from SO_2 emissions from coal-fired power plants in the USA. These are not included in this estimate but then neither is the electricity generated in these American plants. There is no reason to believe that the present normalized estimate is distorted by these emissions.

long-distance effects from SO_2 emissions, are in the lower parts of the best-estimate ranges of Paskievici,[2] 0.3 to 30, and of Niehaus, 3.2 to 22, as given in Table 3, as would be expected. Also, these estimates are slightly higher than the recent best-estimate value of Hamilton [54] for local effects in the eastern USA, of about 15/5 = 3 excess fatalities per GWa, assuming 67% SO_2 removal. Thus, the present estimate has some consistency with the results of Paskievici, Niehaus and Hamilton.

Considering the uncertainties in the present estimate, especially the neglect of long-distance effects, we assume that the ranges of values of Paskievici and of Niehaus for public fatalities from diseases from the coal-fuel cycle include the situation for Canada, which is probably in the lower part of these ranges, especially since the factor of 5 for long-distance effects estimates by Hamilton for the USA would probably be lower for Canada, with its lower population density.

Although, as mentioned earlier, coal transportation distances and methods for coal-fired power plants in Canada may be different than those for which the public fatality rate by accidents, section 4.2.2, were established, we believe that these rates are also applicable to Canada. Some support for this conclusion can be drawn from the work of Hamilton [51], who gives a range of 0.46 to 2.0 fatalities/GWa, for the total of both public and workers, because of accidents in coal transportation to power plants in the USA, assuming a rail trip distance of about 500 km. Trip length and railroad characteristics and practices are similar in Canada and the USA. If the occupational fatalities arising from transport given by Niehaus in Table 2 are added to the public fatalities from transport accidents given by Niehaus and by Paskievici in Table 3, the resulting ranges are 1.02 to 1.88 and 0.92 to 1.76 fatalities/GWa, for Paskieivici and Niehaus respectively, in reasonable agreement with the above range given by Hamilton.

The results of these estimates for fatality rates from coal-fired power plants in Canada are summarized in Tables 7 and 8, where the total best-estimate values of Niehaus and of Paskievici are also given for convenience.

Table 7

Estimates of the Risks of Occupational Fatalities from Diseases and Accidents from the Coal Fuel Cycle in Canada

Stage	Total Fatalities/GWa
Fuel Supply	1.17
Transport	(0.35 - 0.38)*
Operation	(0.016)*
Construction	0.056
Total	1.59 - 1.62
Niehaus (Total from Table 1)	1.18 - 1.28
Paskievici (Total from Table 1)	0.94 - 2.6

* Assumed same as Niehaus figures.

Table 8

Estimates of the Risks of Public Fatalities from Diseases and Accidents from the Coal Fuel Cycle in Canada

Stage	Total Fatalities/GWa
Fuel Supply	-
Transport	(0.46 - 2.0)*
Operation	4 - 5**
Construction	
Total	4.5 - 7.0**
Niehaus (Total from Table 3)	3.77 - 23.4
Paskievici (Total from Table 3)	0.97 - 31.5

* Assumed same as Hamilton figures [51].
** Local effects only.

We conclude from this assessment that both occupational and public fatality rates for coal-fired power plants in Canada lie close to or within the best-estimate ranges given by Paskievici and by Niehaus. While the public fatality rate from emissions may be lower in Canada, there is no real evidence yet to this effect. We thus accept the best-estimate ranges of Paskievici and of Niehaus as being reasonably representative of the probable fatality rates for this fuel cycle in Canada.

5. RISKS OF FATALITIES FROM THE NUCLEAR FUEL CYCLE

Paskievici [6,8,9,10] reviewed the studies of the risks of nuclear power plants and their fuel cycles given in references 14-18, 20-23, 25, 26, 28-30, and 66 and 67. Niehaus and his colleagues [7,11] also reviewed the studies given in references 14, 18 and 21 and, in addition, those in references 31, 32, 34-38, 41-43 and 68. Cohen and Pritchard [5] also reviewed references 14, 15, 18, 21, 23, 25, 28, 45-48, and 50 and, in addition, the work of Black and Niehaus [7].

The ranges of estimates, from these various sources, of occupational fatalities associated with electricity production from the nuclear fuel cycle are given in Table 9, in which the best-estimate values of Paskievici and of Niehaus are also given.

The distributions of the occupational fatalities from diseases in the nuclear industry over the stages of the fuel cycle, given in the various reviews, are summarized in Table 10, in which the best-estimate distributions of Niehaus and of Paskievici are also given. Similarly the distributions of the occupational fatalities from accidents in the nuclear industry are given in Table 11.

Table 9

Occupational Fatalities in the Nuclear Fuel Cycle

(Fatalities/GWa)

Source	Type of Fatality	Range from Literature Reviewed	Best Estimate Mean	Best Estimate Range
Paskievici	Diseases	0.02 - 0.81	0.20	0.13 - 0.30
	Accidents	0.08 - 0.75	0.20	0.13 - 0.30
Niehaus	Diseases	0.028 - 0.92	--	0.42 - 0.49
	Accidents	0.087 - 0.60	0.17	-- --
Cohen and Pritchard	Diseases	0.052 - 0.88	--	-- --
	Accidents	0.08 - 0.86	--	-- --

Table 10

Distribution Among the Stages of the Nuclear Fuel Cycle of Occupational Fatalities from Diseases

(Fatalities/GWa)

Stage	Source	Range from Literature Reviewed	Best Estimate
Fuel Supply* & Reprocessing	Niehaus	0.003 - 0.67	0.28 - 0.3
	Paskievici	0.005 - 0.60	0.05
	Cohen & Pritchard	0.020 - 0.60	--
Transport	Niehaus	0.0008 - 0.115	0.0006
	Paskievici	0 - 0.004	--
Plant Operation	Niehaus	0.024 - 0.14	0.13 - 0.18
	Paskievici	0 - 0.30	0.15
	Cohen & Pritchard	0.032 - 0.28	--
Waste Management	Paskievici	0.074	--
OVERALL	Niehaus	0.028 - 0.92	0.42 - 0.49
	Paskievici	0.02 - 0.81**	0.13 - 0.30
	Cohen & Pritchard	0.052 - 0.88	--

* Includes mining, refining, conversion to UF_6, enrichment, fuel fabrication.

** Extremes of stage ranges are from different sources. Therefore, they do not sum to these values.

Table 11

Distribution Among the Stages of the Nuclear Fuel Cycle of Occupational Fatalities from Accidents

(Fatalities/GWa)

Stage	Source	Range from Literature Reviewed	Best Estimate
Fuel Supply* & Reprocessing	Niehaus	0.071 - 0.57	0.094
	Paskievici	0.074 - 0.57	-
	Cohen & Pritchard**	0.067 - 0.57	-
Transport	Niehaus	0.0026 - 0.015	0.002
	Paskievici	0.003 - 0.013	-
	Cohen & Pritchard	0 - 0.015	-
Plant Operation	Niehaus	0.013 - 0.020	0.014
	Paskievici	0.013 - 0.27***	-
	Cohen & Pritchard	0.013 - 0.27	-
Construction	Niehaus	-	0.055
OVERALL	Niehaus	0.087 - 0.60	0.17
	Paskievici	0.08 - 0.75****	0.13 - 0.30
	Cohen & Pritchard	0.08 - 0.86	-

* Includes mining, refining, conversion to UF_6, enrichment, fuel fabrication.
** Includes reprocessing under Plant Operation.
*** Includes accidents during construction.
**** Extremes of stage ranges are from different sources. Therefore, they do not sum to these values.

The ranges of estimates of public fatalities resulting from the nuclear fuel cycle, from the literature surveyed by Paskievici, Niehaus, and Cohen and Pritchard are summarized in Table 12, which also gives the best-estimate values of Paskievici and of Niehaus. The distributions of the public fatalities from diseases over the different stages of the nuclear fuel cycle are summarized in Table 13. No distributions for the public fatalities from accidents over the different stages of the fuel cycle are shown, since all such fatalities arise from the transportation stage.

The major occupational and public risks associated with the nuclear fuel cycle are latent cancer fatalities from exposures to ionizing radiation.

There is less uncertainty on adverse health effects from the nuclear fuel cycle than on those from the coal fuel cycle because:

a) there is general agreement to use a specific linear dose-response curve, even at low dose levels where conclusive evidence does not yet exist,

b) exposures of workers to radiation are routinely measured accurately, and

c) radioactive emissions from nuclear power plants are continuously monitored.

Other contributing factors are the specificity of radiation effects, the considerable research on radiation damage and repair mechanisms and the extensive knowledge of the various pathways for human exposure to radiation. Thus, as mentioned above, the ranges of uncertainties in occupational and public fatalities from diseases given in Tables 9, 10, 12 and 13 are considerably lower than those for diseases from the coal fuel cycle given in Tables 1 and 3.

While it is generally accepted for regulatory purposes that there is a linear dose-response relation, with no threshold, for low radiation doses at low-dose rates, there has been no clear scientific demonstration of this behavior [68]. Thus, the situation with respect to adverse health effects for low radiation doses may appear to be the same as that for low exposures to sulfates and particulates. However, the uncertainties associated with low radiation doses are less, partly because the mechanisms of harmful effects are better known.

The studies surveyed by Paskievici, Niehaus and Cohen and Pritchard all assume no-threshold, linear dose-response relationships with risk coefficients in the range of $\frac{1}{2}$ to 2×10^{-2} fatal cancers per person-sievert and in the range of 0.5 to 3×10^{-2} serious genetic effects per person-sievert. In general, the effects of collective dose commitments beyond 500 years are ignored or are discounted as in present-worth financial calculations.

Many of the studies reviewed do not consider risks arising from uranium mine tailings or from radioactive waste management. Potential occupational and public fatalities from these activities are discussed later.

Table 12

Public Fatalities in the Nuclear Fuel Cycle

(Fatalities/GWa)

Source	Type of Fatality	Range From Literature Reviewed	Best Estimate Mean	Best Estimate Range
Paskievici	Diseases	0 - 0.53	0.2	0.1 - 0.4
	Accidents	--	0.012	0.008 - 0.018
Niehaus	Diseases	0.014 - 0.36	--	0.27 - 0.32
	Accidents	0.006 - 0.012	--	0.003 - 0.006
Cohen and Pritchard	Diseases	0 - 0.32	--	--
	Accidents	0.0013 - 0.013	--	--

Table 13

Distribution Among the Stages of the Nuclear Fuel Cycle of Public Fatalities from Diseases

(Fatalities/GWa)

Stage	Source	Ranges From Literature Reviewed	Best Estimate
Fuel Supply & Reprocessing	Niehaus	0.001 - 0.13	0.073
	Paskievici	0.001 - 0.21	--
Transport	Niehaus	0.0002 - 0.0012	0.0006
	Paskievici	0.001 - 0.003	--
Plant Operation	Niehaus	0.013 - 0.23	0.19
	Paskievici	0 - 0.23	--
Construction	Niehaus	--	0.008 - 0.057
	Paskievici	0.007 - 0.020	--
Waste Management	Paskievici	0 - 0.25	--
Total	Niehaus	0.014 - 0.36	0.27 - 0.32
	Paskievici	0.002 - 0.53*	0.10 - 0.40

* Extremes of stage ranges are from different sources. Therefore, they do not sum to these values.

Almost all of the studies surveyed are based on the assumption that electricity is generated in light water reactors using enriched fuel. Many also include the risks from fuel reprocessing in the analysis.

As pointed out earlier, the basic assessments of Paskievici, Niehaus and Cohen and Pritchard, as summarized in Tables 9 to 13, do not include risks from large hypothetical accidents. A discussion of risks from low probability, high-consequence accidents in nuclear electricity generation will be provided later, together with the risks of such accidents in the coal fuel cycle and in hydro-electric generation.

5.1 Occupational Risks from the Nuclear Fuel Cycle

As stated earlier, estimates of occupational fatalities in the nuclear fuel cycle are summarized in Tables 9, 10 and 11.

5.1.1 **Occupational Risks from Diseases**

The major occupational risks from diseases occur in uranium mining,[8] from exposure to gamma radiation and radon daughters; in power plant operation, from exposure to activated material and fission products; and, where it is used, in reprocessing of fuel, from exposure to fission products and actinides. Table 10 reflects this situation.

Tables 9 and 10 show that the best-estimate mean value of Paskievici for occupational fatalities from diseases (0.2/GWa) is about half the values given by Niehaus (0.42 - 0.49/GWa).

5.1.2 **Occupational Risks from Accidents**

Table 11 shows that the major occupational risks from accidents occur in the fuel supply stage, i.e., in mining. Note, however, that the fatalities per GWa arising from mining are about an order of magnitude less for the nuclear fuel cycle (0.094/GWa) than for the coal fuel cycle (0.66 - 0.73/GWa, Table 2). The much lower mining fatality rate for the nuclear fuel cycle results mainly, of course, from the much higher energy content per tonne of material mined for average uranium ores as compared to coal.[9]

For the same reason, the occupational risks from transportation are much lower for the uranium fuel cycle (0.002/GWa, Table 11) than for the coal fuel cycle (0.35 - 0.38/GWa, Table 2).

Finally, it should be noted that the best-estimate total occupational accident fatality figure given by Niehaus, as shown in Table 9, includes an allowance for fatalities during construction, which the best-estimate range given by Paskievici does not. Allowing for this difference, the best-estimate value of Niehaus ignoring construction risks (~0.12 fatalities/GWa) agrees with the lower limit of the range of best-estimate values given by Paskievici.

5.2 <u>Public Risks from the Nuclear Fuel Cycle</u>

Estimates of public fatalities in the nuclear fuel cycle are summarized in Tables 12 and 13.

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[8] Part of the uncertainty range in occupational fatalities from diseases in the fuel supply stage in Table 10 arises because of differences of radiation exposures of miners in underground and open-pit mines.

[9] Accident fatality rates per million man-hours are essentially the same for coal and uranium mining in the USA, about one per million man-hours [14]. In Canada, the coal mining fatality rate in 1974 was slightly over one per million man-hours while that for uranium mining was about 0.66 per million man-hours [8].

5.2.1 **Public Risks from Diseases**

As can be seen from the best estimates of Niehaus in Table 13, the major public risks in the nuclear fuel cycle occur from the operation of the power plants themselves, from exposure to fission products and activated material, and at the fuel supply stage, mainly from radioactive releases from uranium mine tailings.

Of course, there is also a public risk associated with the management and disposal of high-level wastes, which was not considered by Niehaus in his estimate of the distribution of risks over the different activities of the fuel cycle [7]. The range of values from the literature given by Paskievici in Table 13 for fatalities from waste management cannot really be used as a guide to the relative hazard to the public from this activity since, as he points out [8,9], the figures given in the various studies for these risks are not comparable. Some are based on reprocessing risks, some are based on effects from uranium mine tailings while others apply to underground storage of high-level wastes.

5.2.2 **Public Risks from Accidents**

The predominant cause of public fatalities from accidents in the nuclear fuel cycle is accidents in transportation of fuel, wastes and other materials. For the reasons given earlier, the best estimate accident fatality rates of Paskievici and of Niehaus, as given in Table 12, are significantly less than those for the coal fuel cycle, as given in Table 3, and are much lower than those attributed to disease in the nuclear fuel cycle.

5.3 **Assessment of the Risks of Fatalities from the Nuclear Fuel Cycle in Canada**

5.3.1 **CANDU Fuel Cycle Technology**

We will now assess the applicability of the foregoing nuclear fuel cycle risk estimates to the situation in Canada. This assessment is more imperative for the nuclear fuel cycle than for the coal fuel cycle since the technology of nuclear power in Canada is quite different from that used in most other countries, while the coal fuel cycle technology used here is essentially the same as that used elsewhere.

With the CANDU natural-uranium fuel cycle, there are no requirements for UF_6 conversion or for enrichment of nuclear fuel.[10] On the other hand, production of heavy water is required for CANDU reactors. The characteristics of the CANDU reactor are quite different from those of the LWR's considered in most other comparative risk studies, and operating practices and the regulatory regime in Canada differ in some respects from those in other countries. The technology of reprocessing of spent natural uranium fuel will differ from that of spent enriched uranium fuel. The Canadian high-level waste management program will have its

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[10] All UF_6 conversion done in Canada is for uranium for export and so should not be considered as part of the nuclear fuel cycle in Canada.

own technology as well as its unique geographical and geological characteristics. All of these differences may result in the risks of the nuclear fuel cycle in Canada being different from those for such cycles elsewhere, as we shall see.

5.3.2 **Risks of Fatalities from Fuel Supply**

5.3.2.1 **Occupational Risks**

Occupational risks in the fuel supply stage of the nuclear fuel cycle in Canada are given in references 69 to 72 in terms of external and internal exposures to radiation.

Frost, et al. [69], estimate a total occupational gamma-ray dose of 5.80×10^{-3} person-Sv and a radon daughter exposured of 0.6 person-WLM per tonne of uranium processed in mining, refining and fuel fabrication in Canada. Assuming fuel burn-up in CANDU reactors of 180 MW(th)h/kgU and cycle thermal efficiency of 29% [73], with risk coefficients of 1×10^{-2} fatal cancers/person-Sv for gamma rays and 300×10^{-6} fatal cancers/person-WLM for radon daughters [74], these data lead to about 0.04 occupational fatalities per GWa from diseases in the fuel supply stage for the nuclear fuel cycle in Canada.

The Health Protection Branch (HPB) of National Health and Welfare [70,71] estimated a total occupational dose in uranium mining, milling, refining and fuel fabrication in Canada in 1978 of 1.00 person-Sv external and 2960 person-WLM internal. In that year, 633 tonnes of uranium were used in Ontario Hydro reactors [75] while 6803 tonnes of uranium were mined in Canada [76]. The uranium used in Ontario Hydro reactors produced 3.3066 GWa of electrical energy in 1978 [75]. Of the 1.00 person-Sv dose, 0.77 person-Sv occurred in the mining, milling and refining stage and thus would be associated with the total amount of uranium mined, while 0.23 person-Sv occurred in the fuel fabrication stage and so would be associated with the fabrication of CANDU fuel only, the great majority of which was for use by Ontario Hydro. All of the 2960 person-WLM exposure to radon daughters occurred in the mining stage. Reducing the 0.77 person-Sv gamma ray dose and the 2960 person-WLM radon daughter exposure in proportion to the fraction of uranium mined which was used in power reactors in Canada while retaining the 0.23 person-Sv gamma ray dose incurred in fuel fabrication, using the same risk coefficients as before, we estimate from the HPB data that total risk of occupational fatalities from diseases in the fuel supply stage for the nuclear fuel cycle in Canada in 1978 would have been about 0.026/GWa, which is of the same magnitude as that estimated from the data of Frost, et al., 0.04/GWa.

Occupational radiation exposures for uranium mining and nuclear fuel processing in Canada for 1984 are given in reference 72. From these data, the total occupational collective doses were calculated to be 33.3 person-sieverts external dose and 3850 person-WLM radon daughter dose for uranium miners and 0.22 person-sieverts external dose for nuclear fuel processors. Using the same risk coefficients as before [74], pro-rating the mining doses by the percentage of mined uranium used domestically in 1984, 17.3% [77], the occupational risks for the fuel supply stage of the nuclear fuel cycle in Canada in 1984 can be calculated knowing that 5.628 GWa of nuclear electricity was generated in Canada in that year [1]. The total risk estimated in this way is about 0.046 fatalities/GWa, somewhat above the values estimated earlier from references 69-71.

These figures are somewhat lower than the estimates, based on world data, of Paskievici, 0.05 fatalities/GWa, and considerably lower than the range, also based on world data, of Niehaus, 0.28 to 0.30 fatalities/GWa, as given in Table 10. Lower Canadian figures might be expected because of the absence of UF_6 conversion and fuel enrichment in the CANDU fuel cycle.

Frost et al [69], give data on total accident rates in uranium mining in Canada, but do not specify fatal accident rates. Reference 78 reports fatality rates in Ontario uranium mines for the period 1970 to 1974 of 63.8 per 10^8 man-hours for miners and 49.5 per 10^8 man-hours for mill workers. Weighting these figures by the numbers employed in both categories, we obtain a production worker fatality rate of 61.1 per hundred million man-hours. All uranium production in Ontario was then, and still is, from underground mines, while about 25% of Canadian uranium production is now from open-pit mines [79], where the miner fatality rate is lower. Donnelly et al [58] report fatality rates for all miners in open-pit mines in Ontario about one-quarter of those for all miners in underground mines. Assuming that this ratio can be applied to all Canadian uranium mines, the miner fatality rate in open-pit uranium mines is estimated as 63.8 x 0.25 = 16.0 per 10^8 man-hours. Weighting the miner and mill-worker fatality rates by the current numbers of 1840 miners and 647 mill workers [79], and weighting the results by the fractions of Canadian uranium currently produced in under-ground and open-pit mines, we estimate an overall production worker fatality rate of about 51 fatalities per hundred million man-hours. This estimate is probably high since it is derived from fatalities in an earlier period (1970-74) and safety practices have improved since then. The total uranium produced in Canada in 1982 was 8075 tonnes of U, by a production work force of 2487 [79]. Assuming that each works 2000 hours per year on the average, the productivity of these workers is about 162,300 tonnes U per hundred million man-hours. Assuming, as above, that fuel burn-up in a CANDU reactor is 180 MW(th)h per kg U and that the net cycle efficiency is 29%, it can be calculated that the occupational fatality rate from accidents is about 0.053 per GWa. This rate is less than the best estimate of Niehaus, given in Table 11, 0.094 fatalities/GWa.

5.3.2.2 **Public Risks**

Public risks from the fuel supply stage of the nuclear fuel cycle in Canada are given in references 69 and 70.

Frost et al [69], give doses for the hypothetically most exposed members of the Canadian public: from uranium mining, < 0.2 mSv/a; refining, < 0.03 mSv/a; and fuel fabrication, < 0.01 mSv/a; for a total effective dose equivalent, including allowance for internally deposited radionuclides of < 0.24 mSv/a in the late 1970's. Noting that this total dose is a relatively small fraction of the average dose from background radiation in Canada, ~2 mSv/a, and that it is within the normal fluctuations in background, they conclude that it is difficult to rationalize the use of these estimates to calculate fatal cancer risks to the Canadian public from the fuel supply stage of the nuclear fuel cycle.

In reference 70, the collective doses for the Canadian public from the fuel supply stage in 1978 are given as 0.12 person-sieverts from mining and milling and 0.09 person-sieverts from uranium refining. Assuming the usual risk coefficient, 10^{-2} fatal cancers per person-sievert, recognizing, as in section 5.3.2.1, that only about 9.3% of the uranium mined in Canada in 1978 was used in Canadian reactors [75,76] and noting that Canadian reactors produced 3.3066 GWa

of electricity in 1978 [75], we can estimate from the above data that the total public risk from the fuel supply stage of the nuclear fuel cycle in Canada in 1978 would have been about 5.9×10^{-5} fatalities per GWa.

This risk is more than three orders of magnitude less than that given by Niehaus in Table 13, 0.073. It is also significantly less than the lower limits of the ranges from the literature surveyed by Niehaus and by Paskievici, as can be seen in Table 13. The reasons for the very low risk estimated for Canada compared to the risks estimated elsewhere are not clear.

5.3.3 **Risks of Fatalities from Transportation**

No information has been found on the risks to workers and the public from transportation of uranium and nuclear fuel in Canada. There is no reason to expect that there would be any great differences in risks in this stage from those estimated elsewhere, as given in Tables 10, 11 and 13 for occupational and public risk, respectively. In any case, the best-estimate values given in these Tables for transportation risk make very small contributions to the total fuel cycle risks so that even large errors in these values would not affect the total cycle risk to any significant extent.

5.3.4 **Risks of Fatalities from Generating Station Operation**

5.3.4.1 **Occupational Risks**

Information on occupational risks from the operation of nuclear power plants in Canada is provided in references 58, 60, 70, 71 and 72.

Radiation doses incurred in the operation of nuclear generating stations in Canada as given in references 58, 70, 71 and 72 are summarized in Table 14. Collective dose data are given directly in three of these references, while reference 72 provides data on the numbers of persons in 12 different occupational categories with annual (1984) doses in each of six different ranges. From reference 72, the collective dose for each occupational category was estimated by assuming that all persons in each dose range received a dose equal to the mean value of the range, multiplying this mean value by the number of persons in the range and summing the resulting values over all of the six ranges. The total collective dose incurred in nuclear generating station operation was then determined by summing the collective doses for each occupational category, except that of construction, which is considered separately.

With the usual exposure risk coefficient, the ranges of occupational doses shown in Table 14 would result in a risk of fatal cancers from the operation of nuclear power plants in Canada of about 0.048 to 0.058 per GWa. This range of values is considerably smaller than the best estimate range of 0.13 to 0.18 fatalities/GWa given by Niehaus, and the best estimate value of 0.15 fatalities/GWa given by Paskievici, as shown in Table 10.

Table 14

Occupational Doses in
Nuclear Generating Station Operation in Canada

Source	Year	Collective Dose, Person-Sv	Energy Generated GWa	Person-Sv/ GWa
Reference 70	1978	18.40	3.3066 [75]	5.56
Reference 71	1978	18.43	3.3066 [75]	5.57
Reference 58	1978	17.77	3.3066 [75]	5.37
	1979	20.66	3.690 [65]	5.60
	1980	19.39	4.062 [80]	4.77
Reference 72	1984	32.57	5.628 [1]	5.79

There have been no fatalities to date resulting from accidents in the operation of nuclear generating stations in Canada [58,60,81]. The total electrical energy generated by nuclear power from 1962, the year that the first power reactor, NPD, went on line to the end of 1984 was about 44 GWa[11]. Assuming that any such fatalities would follow a Poisson distribution, an upper limit to the accident fatality rate (68% confidence) can be estimated as about 0.022 per GWa. This value is somewhat above the best-estimate value of Niehaus, based on world experience, of 0.014 per GWa, as shown in Table 11. Considering that the estimated value for Canada is an upper limit, there is reasonable consistency between these values.

5.3.4.2 **Public Risks**

Information on public risks from the operation of nuclear generating stations in Canada, in terms of total public collective doses, is given in references 70, 81 and 83.

Reference 70 reports a total public collective dose of less than 4.0 person-sieverts from the operation of nuclear power plants in Canada in 1978. In that year, the total nuclear generation in Canada was 3.3066 GWa [75]. With the usual risk coefficient, the estimated total public risk of fatal cancers is calculated to be about 0.012 per GWa.

From information from Wilson [81], for 1984, the total public collective dose from Ontario Hydro nuclear power plants was about 4.0 person-sieverts. The total nuclear electricity generated by Ontario Hydro in 1984 was 4.66 GWa [1]. Therefore, the estimated total public risk of fatal cancers is calculated to be about 0.0086 per GWa from the operation of Ontario Hydro nuclear generating stations in 1984.

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[11] Ontario Hydro, Hydro Quebec and New Brunswick Electric Power data, as given in Reference 82.

For the period 1972 to 1978 inclusive, the total collective dose to the public from the operation of all nuclear generating stations in Canada is estimated to be about 62 person-sieverts [83]. During this period, the total electrical energy produced by these stations was about 14.8 GWa. Therefore, the public risk of fatal cancers from the operation of nuclear generating stations in Canada during this period was about 0.042 fatalities per GWa.

This range of estimates, 0.0086 to 0.042 fatalities per GWa, is considerably lower than the best estimate value of Niehaus, 0.19, as given in Table 13. It should be noted also that the estimates for more recent years are less than those for earlier years.

5.3.5 **Risks of Fatalities from Construction**

The only information available on the risks arising from the construction of nuclear power plants in Canada is for occupational risks [60,72], so only these are considered here. We will assume that public risks are as estimated by Niehaus.

Information on the radiation doses of construction workers[12] is provided in reference 72, which gives the numbers of workers in 1984 with doses in each of six different ranges. As before, the collective dose was estimated by assuming that all persons in a given range received a dose equal to the mean value of the range, multiplying this mean value by the number of persons in the range and summing the resulting values over the six ranges. The resulting collective dose for 1984 was 3.94 person-sieverts, which represents a risk of cancer fatalities of about 0.039 for the year.

This risk should be added to the risks for the other years required to construct a given plant to find the total risk of fatal cancers for workers associated with the construction of a nuclear generating station. This total risk should then be normalized by the total electrical energy that will be produced by the plant over its lifetime.

In 1984, a total of 4030 MW of nuclear generating net capacity was under construction in Canada as additional units at a given generating station or as a second station at a given site [84]. Assuming that this capacity requires an average of nine years to complete [73] and that the average risk per year is the same as that estimated for 1984, the total risk of fatal cancers to construction workers because of radiation exposure would be 0.351 fatalities to complete the 4030 MW under construction. Assuming a plant lifetime of 40 years, as is now done by Ontario Hydro [80], and a lifetime capacity factor of 0.75, a conservative figure for Ontario Hydro nuclear generating stations [80], the total lifetime energy production from this capacity would be about 1.06×10^9 MWh or 120.9

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[12] Construction workers may be exposed to radiation during the construction of multi-unit plants after the first unit has started up or during the construction of a second plant at the same site as that of an existing plant.

GWa. Therefore the risk of fatal cancers from radiation exposure of construction workers on nuclear power plants in Canada is about 2.9×10^{-3} fatalities per GWa. This value is conservative since it applies only to the construction of subsequent units at a multi-unit plant or subsequent plants at a given site.

Hamilton and Wilson [60] report fatal accident rates in the construction of Ontario Hydro nuclear generating stations. In the period 1970 to 1979, six fatal accidents occurred during the construction of 5100 MW capacity, equivalent to a fatality rate of 9.4 in 10^8 man-hours. Making the same assumptions as in the estimate of the risk of cancer fatalities from radiation for construction workers, the lifetime energy production from this capacity would be about 1.34×10^9 MWh or 153 GWa. The risk of fatal accidents during construction of Ontario Hydro nuclear generating stations is then about 0.039 fatalities per GWa. We assume that this risk is applicable to all nuclear generating stations constructed in Canada. This risk is somewhat less than that given by Niehaus, 0.055 fatalities per GWa, as shown in Table 11.

5.3.6 Risks of Fatalities from Waste Management

Extensive studies of the occupational and public risks of nuclear waste management in Canada have been undertaken considering both uranium mine tailings [e.g. 85] and high-level waste disposal [e.g. 86].

The risks associated with mine tailings have been included in those of uranium mining in section 5.3.2.

The risks associated with high-level waste disposal have been expressed to date in predictions of the dose received by the most-exposed individual, not in terms of collective dose. However, the estimated doses received by the most-exposed individual are very low, typically in the range of 0.01 to 0.1 mSv/a [86], a small fraction of background dose (~2 mSv/a), for a high-level waste repository containing 350 MT of fuel, which would have produced about 2000 GWa of energy. Furthermore, such estimates indicate that the maximum exposure of an individual will occur most frequently at about 8000 years after closure of the facility [87]. UNSCEAR, in its 1982 report [88] predicts even longer periods before any significant collective effective dose commitments arise from high level nuclear waste repositories; UNSCEAR predicts no effects by 10,000 years and a total integrated effect of 30 person-sieverts per GWa, i.e. about 0.3 cancer fatalities per GWa, after one million years.

Therefore, it is not expected that collective dose equivalents from high-level waste management will be very significant, and the resulting risks can be ignored as a contributor to the overall nuclear fuel cycle risk.

Decommissioning of a nuclear power plant at the end of its service life will involve the handling, storage and disposal of various types of radioactive wastes. Little information exists on occupational and public risks associated with decommissioning but some estimates are now becoming available [150,151]. An assessment of these estimates shows that decommissioning risks should not affect the total occupational and public risks of the nuclear fuel cycle in Canada to any significant extent.

5.3.7 **Risks of Fatalities from Heavy Water Production**

The operation of CANDU power reactors requires the production of heavy water for the moderator and the coolant. Heavy water is produced commercially in Canada using the Girdler-Sulphide (GS) dual-temperature exchange process, which utilizes hydrogen sulfide (H_2S) gas flowing counter-current to the water being processed. Hydrogen sulfide is a toxic material which can cause human fatalities at relatively low concentrations. There have been no public fatalities caused by releases of H_2S gas from heavy water production plants in Canada, nor have there been any occupational fatalities, although one worker suffered permanent brain damage from over-exposure to H_2S [83]. We can use this record and that of D_2O production plants in the USA to estimate an upper limit for the normalized risks to the public from the normal operation of GS-process heavy water plants.

In the four D_2O production plants in North America that have operated for any significant periods, there have been no occupational nor public fatalities in about 65 plant-years of operation to date. Assuming a Poisson distribution, we estimate an upper-limit probability of about 0.015 fatalities per plant year, based on this record. The heavy water inventory in a typical CANDU is about 0.9 Mg/MW. Assuming a power plant lifetime of 40 years at a capacity factor of 75%, as before, the inventory requirement per GWa is 30 Mg/GWa. The net heavy water losses, allowing for up-grading, in the Pickering-A NGS (2060 MW capacity) have averaged about 28 Mg/year [141]. Assuming that these net losses are typical for CANDU power plants and are made up by D_2O from a heavy water production plant, the operational heavy water requirements are about 18 Mg/GWa for a total of about 48 Mg/GWa. Assuming full production from the Bruce heavy water plant (BHWP), with a capacity of 720 Mg/year, and assuming that the estimated upper limit fatality rate of 0.015 per plant year applies to the BHWP, the upper-limit estimate of public and occupational risk from normal operation at a heavy water production plant is about 10^{-3} fatalities/GWa.

This estimated risk is negligible compared to the other risks associated with the CANDU fuel cycle.

5.3.8 **Summary of Estimated Risks of Fatalities from the Nuclear Fuel Cycle in Canada**

The foregoing estimates of the risks of the nuclear fuel cycle in Canada are summarized in Table 15, for occupational risks and in Table 16, for public risks. In cases where data were lacking for Canada, but where it is judged that the "world" risks of Paskievici and Niehaus probably apply in Canada also, these risks are shown in Table 15 and 16 in brackets. Small additional risks exist from power plant decommissioning but these are well within the uncertainties in Tables 15 and 16. For convenience, the best-estimate total values of Niehaus and Paskievici, from Tables 9 and 12, respectively, are also shown in Tables 15 and 16.

Table 15

Estimates of Risks of Occupational Fatalities from the Nuclear Fuel Cycle in Canada

(Fatalities/GWa)

Stage	Diseases	Accidents
Fuel Supply	0.026 - 0.046	0.053
Transport	(0.0006)*	(0.002)*
Plant Operation	0.048 - 0.058	0.022
Construction	0.0029	0.039
Waste Management	~0	~0
Heavy Water Production	0.001	--
Total	0.079 - 0.109	0.116
Niehaus (Table 9)	0.42 - 0.49	0.17
Paskievici (Table 9)	0.13 - 0.30	0.13 - 0.30

* Assumed same as Niehaus figures.

Table 16

Estimates of Risks of Public Fatalities from the Nuclear Fuel Cycle in Canada

(Fatalities/GWa)

Stage	Diseases	Accidents
Fuel Supply	5.9×10^{-5}	-
Transport	(0.0006)*	(0.003 - 0.018)**
Plant Operation	0.0086 - 0.042	-
Construction	(0.008 - 0.057)*	-
Waste Management	~0	~0
Heavy Water Production	0.001	-
Total	0.0182 - 0.1006	0.003 - 0.018
Niehaus (Table 12)	0.27 - 0.32	0.003 - 0.006
Paskievici (Table 12)	0.1 - 0.4	0.008 - 0.018

* Assumed same as Niehaus figures.
** Assumed same as overall Niehaus and Paskievici range in Table 12, since public fatalities from accidents occur only in transportation.

It is evident from Table 15 that the estimates for occupational risks from diseases in the nuclear fuel cycle in Canada are about five times lower than those of Niehaus but almost overlap those of Paskievici. The estimated occupational risk from accidents in the nuclear fuel cycle in Canada is about 30% lower

than that of Niehaus and is somewhat below the lower limit of those of Paskievici. It is interesting to note that Hill [53] has estimated total occupational fatality rates from diseases and accidents for the nuclear fuel cycle in Canada of 0.153 to 0.237 fatalities/GWa, which are in agreement with our estimates of total occupational fatality rates for the nuclear fuel cycle in Canada from Table 15 of 0.195 to 0.225 fatalities/GWa.

Table 16 indicates that the estimated public risks from diseases in the nuclear fuel cycle in Canada are less than the best estimate values of Niehaus and of Paskievici. This difference requires further assessment and is presented here on a tentative basis. The public risks from accidents in Table 16 are simply taken from the estimates of Niehaus and of Paskievici and so obviously agree with them.

We conclude from this estimate that occupational and public fatality risks for nuclear power plants in Canada may be less than the best-estimate values of Paskievici and Niehaus. However, our assessment of the risks of the CANDU nuclear fuel cycle has, necessarily, been limited in scope and depth and further, more detailed study is needed. In the circumstances, we use the best-estimate ranges of Paskievici and of Niehaus for the nuclear fuel cycle risks in Canada.

6. RISKS OF FATALITIES FROM THE HYDRO-ELECTRIC SYSTEM

As mentioned earlier, Paskievici, Niehaus and Cohen and Pritchard do not consider the risks of hydraulic generation of electrical energy. As indicated in section 3. of this report, the only recent studies of the risks of this technology which were identified are those of Inhaber [3] and Holdren et al [4] and these have been used as the basis for our estimates here.

Estimating the risks of hydraulic power plants presents several difficulties which are of a different nature than those encountered in estimating the risks of coal and nuclear power plants:

a) The absence of a fuel cycle means that risks arise from acquisition of materials, construction, transportation (associated with materials and construction) and operations and maintenance.

b) Dams and control structures vary considerably in size and type depending not only on the capacity of the hydro-electric power plant but also the topography and geology of the location, so that materials acquisition, construction and transportation risks, which are dominant for these plants, can vary significantly even for plants of the same capacity.

c) Since most hydro-power sites close to load centres in Canada have been fully-developed, new hydro-power sites will generally be located far from load centres so that risks associated with the construction and operation of transmission lines will be more significant with new hydro plants than with new coal and nuclear plants.

d) Since we are excluding consideration of catastrophic accidents in this section of the report, the only significant risks to the public arise from transportation accidents in materials acquisition and in construction.

e) Occupational risks arise almost entirely from accidents.[13]

Considering points d) and e) we will make no attempt to distinguish between fatalities from accidents and from diseases for hydraulic power plants, as was done for coal and nuclear power plants.

Occupational fatality risks from hydraulic power plants, distributed over various activities, as estimated by Holdren et al [4], and by Inhaber [3] are given in Table 17.

Public fatality risks from hydro-electric power plants are estimated by Inhaber for dam failures only and thus, being catastrophic risks, are not considered at this time. Holdren et al, [4] conclude that public risks for hydro-electric plants arise mainly from the transportation of materials, and they estimate the resulting risk to be between 0.03 and 0.22 fatalities/GWa.

Table 17

Occupational Fatalities Associated with Hydraulic Power Plants

(Fatalities/GWa)

	Holdren et al[4]	Inhaber[3]	Inhaber Revised (see Sect.6.1)
Materials Acquisition*	0.0031 - 0.013**	0.064	0.0122 - 0.129
Construction	NA	0.83 - 1.93	0.83 - 1.93
Transportation	NA	-- ***	-- ***
Operations & Maintenance	NA	0.63	0.63
Total	0.16 - 0.26	1.5 - 2.6	1.47 - 2.69

* Includes metal fabrication.
** Calculated from information in Tables 1 and 3 of reference 4.
*** Inhaber discusses some estimates of occupational fatality risks in transportation, but provides no final estimate in his summary table.
NA Not available.

We will now consider and assess these estimates of occupational and public risks from hydro-electric generation and will draw conclusions as to the applicability of these estimates to risks of hydro-electric power in Canada.

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[13] Risks of diseases arise only from emissions associated with acquisition of materials and are very small [3].

6.1 Occupational Risks

As can be seen from Table 17, there is an order-of-magnitude difference between the total risks of hydraulic generation estimated by Holdren et al, [4] and by Inhaber [3].

Holdren et al [43] criticize the estimates of Inhaber, as given earlier in reference 21,[14] on several points. Under materials acquisition, Holdren et al point out that the quantities of materials given by Inhaber may apply to certain Ontario Hydro hydraulic plants but cite considerably different data obtained from two other sources. Holdren et al also point out that Inhaber confused cement and concrete requirements, that he assumed anthracite coal instead of soft coal was used in steel-making and that he treated structural and reinforcing steel as fabricated metal products; these differences would result in Inhaber's risk estimates for materials acquisition being too high.

Under transportation, Inhaber assumed that all material required would be transported 300 miles, while Holdren et al point out that almost all of the material, i.e., rock, earth and aggregate, will be transported only very short distances. This discrepancy resulted in an over-estimate of risks from transportation. The deletion of transportation risks from Inhaber's final tabulation of occupational risks, as noted in footnote 14, was apparently made after recognition of this discrepancy.

In the other categories of occupational risk, Holdren et al [43] do not disagree with the estimates of Inhaber, but believe that the data base is too limited for the estimated risks to be very reliable.

We have revised Inhaber's estimates of risks from materials acquisition in the light of the criticisms of Holdren et al, assuming a 50-year power plant lifetime and an overall capacity factor of 0.60, as assumed by Inhaber. This revision gives a value of 0.0122 fatalities/GWa instead of Inhaber's value of 0.064.

We have also redone the estimates using the two other materials requirements cited by Holdren et al, and obtained values of 0.023 and 0.129 fatalities/GWa. Thus, we show in the last column of Table 17 an overall range of 0.0122 to 0.129 fatalities/GWa.

We have made no attempt to revise Inhaber's earlier estimate of risks from transportation, since he himself ignored these risks in the final version of his work.

Thus, the only change in the revised estimates of Inhaber is in the materials acquisition category, where the revised range slightly overlaps the range of Holdren et al, although the maximum value in this range is an order of magnitude

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[14] Inhaber's estimates in reference 21 are the same as those in reference 3, as given in Table 17 except for the inclusion of transportation risks of 0.33-1.0 fatalities/GWa, which are excluded in reference 3.

higher than that given by Holdren, et al. Nevertheless, this change makes only a slight difference in the total occupational risk estimated by Inhaber, which remains about an order-of magnitude larger than that of Holdren et al.

6.2 Public Risks

From the assessments of Inhaber [3] and Holdren et al [4], the only significant public risks from hydraulic generation, other than hypothetical high-consequence risks of dam failures, arise from the transportation of materials.

While Inhaber gives no final quantitative estimate of public risks from transportation, Holdren et al provide an estimate of 0.03 to 0.22 fatalities/GWa, as noted earlier. To arrive at this estimate, they assumed that public risks are proportional to ton-miles of material moved. They also assumed that sand and cement required for concrete move an average distance of 30 miles and that all other manufactured materials move an average distance of 300 miles.

6.3 Assessment of the Risks of Fatalities from the Hydro-electric System in Canada

6.3.1 Occupational Risks

We will now assess the applicability of the foregoing occupational risk estimates for hydro-electric generation in the Canadian scene. In this case, the situation is somewhat different from that for the coal and nuclear fuel cycles since the estimates of Inhaber are based in part at least on Canadian data. In his estimates, the results for materials acquisition and the lower limit for construction are based on Ontario Hydro data [89].

We will use the data of Inhaber, treated as described earlier, to estimate the risks of materials acquisition under Canadian conditions. As reported earlier, the resulting risk is 0.0122 fatalities per GWa. However, to indicate the uncertainty in this estimate because of large variations in the materials requirements for different hydraulic plant sites, we will also note the range of risks from materials acquisition estimated from the ranges of materials cited by Holdren et al [4], of 0.023 to 0.129 fatalities/GWa.

For construction risks, Inhaber's Ontario Hydro figure was supplemented by information provided by Wilson [81], who reports 62 fatalities in the construction and operation of Ontario Hydro hydraulic plants over the period 1947 to 1985. He also notes that improvements in safety practices over this period have resulted in a steady decline in the accident rate. The electrical energy generated in these plants in this period was 127.5 GWa [81]. To estimate the construction risks per GWa from these figures, we must subtract the fatalities during operation and maintenance from the total given by Wilson and we must also make an allowance for future electrical generation from these plants.

An estimate of the operation and maintenance (O & M) fatalities can be obtained from Hamilton and Wilson [60]. They report that during Ontario Hydro hydraulic plant operation from 1970 to 1979, one fatality occurred, which gives a risk of 0.024 fatalities/GWa. Therefore, if we assume that this fatality rate has remained constant over the period 1947 to 1985, which is not so as noted above, the total estimated fatalities in operation and maintenance over this period

would be about 3, which would imply a total of 59 fatalities in construction. It is difficult to take account of the improvement in safety practices over this period. Safety improvement would be expected mainly to reduce O & M fatalities. Since the estimated O & M fatality rate was based on experience in the last part of this period, the rate in the earlier part would be expected to be higher, so that the operational fatalities would probably be greater than 3 and the construction fatalities would be less than 59. We can thus assume that the estimate of 59 is an upper limit. It is also a conservative figure because it is based on past practices; it would be expected that construction risk associated with new plants would be lower.

Two methods were used to estimate the energy generated by these hydraulic plants. From reference 90, which gives the completion dates for Ontario Hydro hydraulic plants, it was estimated that the total capacity of all the hydraulic plants constructed in the period 1947 to 1985 is 5240 MW. From references 65, 75, 80, 91 and 92, the recent annual average electrical energy output from all Ontario Hydro hydraulic power plants was found to be 4.16 GWa/a from an average total installed capacity of 6490 MW, which gives an average annual capacity factor of 0.64. Assuming that those plants constructed since 1947 have this same capacity factor, the total annual electrical energy output from the newer plants would be about 3.35 GWa/a. Ontario Hydro estimates the service life of hydraulic plants to be 65 to 100 years [92]. The oldest of the plants constructed since 1947 are approaching 40 years of service, so that at least 25 years of additional service would be expected from these plants and longer periods for the later plants. To be conservative, we assume that all hydraulic plants constructed since 1947 have 25 years of service life remaining so that the estimated future energy generation from these plants is 25 x 3.35 = 83.8 GWa. Adding this value to the energy generated until the end of 1985, 127.5 GWa, as given earlier, the total estimated energy output over the lifetime of these plants would be about 211 GWa. In the other method, we assume that the 5240 MW capacity of these newer plants would have the minimum estimated service life of 65 years and would operate at the above-estimated hydraulic system capacity factor of 0.64. Therefore, the total energy generated by these plants would be 5240 x 65 x 0.64/1000 = 218 GWa. These two estimates agree well, and we use the lower figure, 211 GWa, to estimate the normalized construction fatality risk.

Therefore, the estimated construction risk for hydraulic generating plants in the Ontario Hydro system is 59/211 = 0.28 fatalities/GWa. This risk is considerably lower than the low end of the range given by Inhaber, 0.83 fatalities/GWa, which was based on earlier data from Ontario Hydro. It is almost an order-of-magnitude lower than the upper end of the range given by Inhaber, which represents experience in France. We will assume that the estimates based on Ontario Hydro experience are typical for Canadian utilities and will thus assume a range of 0.28 to 0.83 fatalities/GWa for construction risks in Canadian hydro-electric generation.

As noted earlier, Inhaber made no estimate of occupational fatalities from transportation in the final version of his work. To assess these risks for Canadian conditions, we assumed that all materials used in constructing a hydro-electric plant except for rock, sand and gravel would be transported 300 miles on the average.

The quantities of materials transported were based on the data provided by Morison for Ontario Hydro hydraulic stations [89] using the revised methods discussed earlier.

Assuming that risks are proportional to ton-miles,[15] so that we can use the same risk factors as Inhaber used for coal transportation, we estimate that occupational transportation risk is in the range of 0.01 to 0.03 fatalities/GWa. If the ranges of materials cited by Holdren et al [4] are assumed in the analysis, the range of occupational transportation risk expands to cover a range from 0.005 to 0.10 fatalities/GWa.

As mentioned earlier, since most new hydro-power sites in Canada will be located far from load centres, risks arising from the construction and maintenance of transmission lines will be more significant for hydro-electric plants than for coal and nuclear plants. Risks associated with transmission lines will be mainly occupational. The only public risk of significance would seem to be from transportation of materials, as for hydro-electric plants themselves, but because of the generally remote locations of these lines, and the lower quantities of materials required compared to those for the power plants, we assume that the incremental risk to the public from the longer transmission lines required for hydraulic plants compared to coal and nuclear plants is negligible.

Inhaber gives some information on occupational risks associated with transmission lines [3]. He attributes most of the risk to construction, with materials acquisition, transportation and maintenance making smaller contributions. The information provided by Inhaber cannot readily be converted to normalized risks per GWa as for other risks considered in this report, as it is given in terms of fatalities per kilometre for lines of different voltages, without reference to line capacity.

However, based on estimates for the Hydro-Québec transmission lines from the La Grande plants of the James Bay development, Inhaber concludes that the total occupational and public risk arising from transmission lines adds about 2% to 3% to the total risk of hydro-electricity. Accepting this estimate, we conclude that the incremental occupational risks because of transmission lines is within the uncertainty of the total estimated occupational risk for hydro-electric power plants and we make no special allowance for it.

The occupational risk during operation and maintenance in Ontario Hydro hydraulic plants is given by Hamilton and Wilson [60] as 0.024 fatalities/GWa. This risk is much below that given by Inhaber, for experience in France, of 0.63 fatalities/GWa.

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[15] Note that Holdren et al [4] assume that occupational transportation risks are proportional to the total tons moved rather than to ton-miles on the basis that most occupational accidents occur when loading or unloading materials or in rail freight yards and other activities independent of the distance the material is moved.

The foregoing estimates for Canadian conditions are based mainly on Ontario Hydro experience. How representative these estimates are of all Canadian utilities is not certain, but some perspective can be obtained by noting in Table 18 total fatal accident rates in some Canadian utilities.

TABLE 18

Total Occupational Fatality Rates in Some Canadian Utilities

(Fatalities/10^8 person-hours)

Utility	Fatality Rate	Years	References
Ontario Hydro	9.9	1970-79	[60]
Manitoba Hydro	4.8	1970-79	[60]
British Columbia Hydro	10.8	1970-79	[60]
New Brunswick Electric Power Commission	11.5	1970-79	[60]
Hydro Québec	4.0*	1980-87	[154]

* Excludes fatalities in construction

These rates represent fatalities in all activities in the utilities and not just those associated with hydraulic generation. Nevertheless, the above figures suggest that the Ontario Hydro occupational fatality rate is close to the average (8.2 fatalities/10^8 person hours) of these Canadian utilities, so that the estimates developed here for occupational risks in hydraulic power generation may be assumed to apply for all Canadian utilities, recognizing the uncertainties in all the data.

The foregoing estimates for occupational fatalities for hydro-electric power plants under Canadian conditions are summarized in Table 19, where the total estimates of Holdren et al and the revised total estimates of Inhaber are also shown for convenience.

The results in Table 19 lie between the estimates of Holdren et al and the revised estimates of Inhaber, but are closer to those of Holdren et al.

Table 19

Estimates of Risks of Occupational Fatalities from Hydraulic Generation in Canada

(Fatalities/GWa)

Stage		
Materials Acquisition	0.0122 [89]	0.023 - 0.129, [4]
Construction	0.28 - 0.83	0.28 - 0.83
Transportation	0.01 - 0.03 [89]	0.005 - 0.10, [4]
Operation & Maintenance	0.024	0.024
Total	0.326 - 0.896	0.332 - 1.08
Holdren et al (Table 17)	0.16 to 0.26	
Inhaber revised (Table 17)	1.47 to 2.69	

It is evident from Table 19 that construction risks dominate the occupational risks for hydraulic power plants in Canada, so that the many uncertainties in the other stages do not result in large uncertainties in the total risks.

6.3.2 **Public Risks**

We assume, after Holdren et al [4], that the only significant non-catastrophic public risks from hydraulic generation in Canada arise from transportation of materials.[16]

We estimate the public risks from transportation by assuming that all materials except rock, sand and gravel would be moved on the average 300 miles, as was done in estimating occupational transportation risks. We assume that risks are proportional to ton-miles of materials moved. Once again, we assume that the risk coefficients used by Inhaber for public fatalities for coal transportation can be used here.

The quantities of materials assumed are based on those given by Morison [89] for Ontario Hydro hydraulic plants. Again, to provide perspective on the uncertainty in this estimate the ranges of materials noted by Holdren et al [4] are also used in the estimates. The results are summarized in Table 20, where they are compared to the estimates of Holdren et al. Table 20 shows that the upper end of the present range based on materials data from Ontario Hydro [89] is about a factor of three lower than the lower end of the range given by Holdren et al. However, the risk range estimated from the variations in materials noted in reference 4 overlaps somewhat the range of the Holdren estimates themselves.

Table 20

Estimates of Risks of Public Fatalities
from Hydraulic Generation in Canada

(Fatalities/GWa)

Stage		
Materials Acquisition	--	--
Construction	--	--
Transportation	0.005 - 0.012*	0.0027 - 0.039**
Operation and Maintenance	--	--
Total	0.005 - 0.012*	0.0027 - 0.039**
Holdren et al [4]	0.03 - 0.22	

* Based on materials from reference 89
** Based on materials range from reference 4

[16] Public risks from hydro-electric developments can arise from pollutants, such as mercury released by flooding or river diversions. Insufficient information is available for any meaningful calculations of risks from such sources.

7. RISKS OF FATALITIES FROM CATASTROPHIC ACCIDENTS

7.1 Definitions and Approach

So far in this report, we have dealt with the risks of energy systems during normal operation, which is defined to included minor system upsets and minor accidents of varying severity.[17]

We now examine the risks associated with catastrophic accidents in these energy systems.

A catastrophic accident may be defined as any calamity, disaster or misfortune, usually sudden. Different organizations use different criteria to classify an event as catastrophic. For example, the US National Safety Council uses 25 or more fatalities as the criterion of a catastrophe [93], while the US Department of Commerce uses five or more fatalities [94]. A UKAEA study considers 20 or more fatalities resulting from a single event to constitute a catastrophe [95]. Rowe defines a catastrophic accident as one involving 10 or more deaths, 30 or more injuries or $3 million or more material damage [96].

In considering the risks of catastrophic accidents separately from those of normal operation, we are following the general approach taken by other investigators in this field such as Cohen and Pritchard [5], Paskievici [6], Black and Niehaus [7], Inhaber [3,28] and Smith et al [97].

The main reasons for considering risks from catastrophic accidents separately from those of normal operation are that:

a) there have been few catastrophic accidents associated with energy systems, so that there are insufficient data for meaningful statistical analyses, in general,

b) there have been very few analytical studies of the risks of hypothetical, high-consequence accidents, except for those for nuclear power plants,

c) many perceive a single low-probability accident with a large number of potential fatalities as much more serious than a large number of routine accidents each with only a few fatalities but having the same total fatalities [98].

Mainly for reasons a) and b) above, the approach used for the assessment of the risks from catastrophic accidents in this report will be primarily qualitative and descriptive. First, we cite major accidents associated with coal, nuclear and hydro-electric systems that have occurred, whether or not they meet any of

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[17] Although we have, to the best of our knowledge, excluded risks associated with catastrophic accidents in our assessment to this point, the line between minor and catastrophic accidents is not always clearly drawn in many of the studies we have examined, so that in some cases, the risks that we have estimated for normal operation may include some risks from catastrophic accidents.

the foregoing definitions of a catastrophe, and provide information on the total fatalities caused, both public and occupational.

Next we discuss briefly, where available, general conclusions from probabilistic risk analyses (PRA) of hypothetical accidents for these energy systems. A probabilistic risk analysis is a comprehensive analysis of all identified accident sequences, using experimental data and analytical simulations to predict consequences, and using the known reliabilities of components and frequencies of events to predict probabilities. The most meaningful way in which to present the results of a PRA, as recommended, for example in reference 99, is by means of "risk curves", i.e., complementary cumulative probability distribution function (CCDF) curves, as given in the Reactor Safety Study (Rasmussen Study) [100] and elsewhere, rather than by citing a single overall risk number.

Finally, we assess qualitatively the relevance of this information to these energy systems in Canada.

We now proceed to discuss catastophic accidents associated with the coal, nuclear and hydraulic energy systems.

7.2 Catastrophes in the Coal Fuel Cycle

7.2.1 Serious Accidents That Have Occurred

Accidents causing large numbers of public deaths that can be attributed, at least partly, to the coal fuel cycle include the severe air-pollution episodes referred to in section 4.2.1 and collapses of mine waste piles.

The most severe air-pollution episode occurred in London, England, in December, 1952, when emissions of SO_2 and particulate matter, combining with a dense fog persisting for four days resulted in about 2500 to 4000 excess deaths shortly afterwards [47,52,53]. Other disastrous air-pollution episodes have occurred. Information on some of the more severe incidents is given in Table 21. While the emissions in these incidents emanated from many sources, for example, in the London episodes mainly from the burning of soft coal in domestic grates, these incidents demonstrate the potential public harm, under adverse weather conditions, from coal-burning devices, including coal-fired power stations. With present emission and air pollution regulations, it is highly unlikely that such serious incidents will occur again in the industrialized countries.

Table 21

Air-Pollution Catastrophes*

Location	Date	Excess Fatalities**	Reference
Meuse Valley, Belgium	1930	60	[52,53]
Donora, Pennsylvania	1948	17	[52,53]
London, England	1952	2500-4000	[52,53]
New York	1952	360	[101]
London, England	1956	1000	[52,53,101]
London, England	1962	850	[52,53,101]
Osaka, Japan	1962	60	[101]
New York	1966	168	[101]

* The relative contribution of coal-fired power plants to these incidents is not known.

** Early fatalities only - delayed fatalities are unknown.

With respect to collapses of coal-mine waste piles, the most serious caused 144 deaths in 1966 at Aberfan, Wales [5]. Such collapses can occur only where past practices have permitted coal waste piles to be sited close to residences, schools and other buildings; proper control of siting will prevent such disasters. Other serious coal-related accidents that have occurred are spontaneous combustion of wastes with consequent explosion of accumulated gas and subsidence of abandoned mine workings [5].

The only significant cause of catastrophic occupational fatalities in the coal fuel cycle is a serious mining accident. The frequency of catastrophic mining accidents has decreased in recent years [5,94]. Moreover, although coal mining disasters in the USA often resulted in 200 to 300 fatalities or more per accident in the early part of this century [93], recent data indicate the average fatality rate per disaster in all types of mining and quarrying in the USA was less than 20 over the period since 1951 [94].

7.2.2 Hypothetical Catastrophes

In the coal fuel cycle, the only analysis of hypothetical catastrophic accidents that we have found is a study cited by Cohen and Pritchard [5] of serious accidents associated with the rail transport of coal in the UK. The accidents considered ranged from the collision of a passenger train with a derailed coal train causing 20 or more deaths with a calculated probability of 0.3×10^{-4} per year to a collision between a coal train and a train carrying dangerous material

(e.g., chlorine) in a tunnel with a passenger train then colliding with the wreckage, killing up to 600 passengers with a calculated probability of about 10^{-8} per year.

It has been postulated that the combustion of fossil fuels, including the burning of coal in power plants, could lead to a warming of the atmosphere, through the greenhouse effect. This environmental effect could lead to climatic changes in which large numbers of human lives might be at risk. However, we do not consider this hypothetical catastrophe here because the evidence to support it is far from clear now and any changes would develop slowly, permitting appropriate counter-measures to be taken.

7.2.3 Assessment for Canada

A major air-pollution accident leading to many excess deaths has not occurred in Canada, as far as we are aware; present environmental practices and regulations make the occurrence of one virtually impossible today.

It is also believed that collapse of coal-mine waste piles, explosions resulting from spontaneous combustion of coal-mine wastes or subsidence of abandoned coal-mine workings do not present any real risks of catastrophes in Canada, mainly because of present siting and environmental controls.

Although catastrophes have occurred in underground coal mines in Canada, their frequency and the numbers of fatalities per accident have decreased in recent years [8]. Moreover, most coal is mined here now in open pit mines (Table 5), where the risk of catastrophic accidents would be expected to be less than in underground mines. Thus, the present risk of catastrophic occupational accidents in the coal fuel cycle would be expected to be very low in Canada.

7.3 Catastrophes in the Nuclear Fuel Cycle

7.3.1 Serious Accidents That Have Occurred

There have been only two reactor accidents in which immediate or near-term fatalities have occurred, the SL-1 accident in the USA in 1960, in which two plant workers were killed by blast, and the Chernobyl-4 accident in the USSR in 1986, in which 31 plant and emergency workers were killed, two by blast or impact, the remainder by acute radiation doses (4-16 sieverts). There have been no public fatalities from acute radiation doses in these accidents nor in any other reactor accidents.

However, there have been a few reactor accidents in which fuel damage has occurred and/or in which some radioactive material has been released to the building or to the environment. These accidents[18] are listed in Table 22, together with the SL-1 and Chernobyl-4 accidents. For completeness, such accidents in research or test reactors and in reactors used for military purposes

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[18] The accident to the Brown's Ferry reactor involved neither core damage nor release of radioactive material, but is included here because it is generally considered a serious accident.

are included in Table 22, although it could be argued that, to be consistent with the approach used in this report, only accidents to current-technology power reactors should be considered. This more complete listing then includes, in addition to the SL-1 accident, the accident to the Windscale 1 reactor in the UK, which was a graphite-moderated, gas-cooled reactor used for plutonium production for military purposes. This accident was the most serious reactor accident until the Chernobyl accident and it provides perspective on large radioactive releases in a power reactor.

Listing in Table 22 of accidents other than those at SL-1 and Chernobyl-4 does not imply, of course, that any of these other accidents should necessarily be considered catastrophes. However, since exposure to low levels of radioactive material is assumed to increase the risk of cancer and since fuel damage increases the risk of radioactive releases, it was decided to consider these accidents as serious.

While we have attempted to list all "serious" reactor accidents in Table 22, there may have been others of which we are not aware. There have also been other accidents resulting in fuel damage for which insufficient information was available to permit listing in Table 22 [152].

Only in the cases of Windscale-1, Three Mile Island-2 and Chernobyl were there measurable or significant public radiation doses, as can be seen in Table 22. The collective public dose of 2,000 person-sieverts shown in Table 22 for the Windscale accident would be expected, using the usual risk coefficient, to result eventually in an upper limit risk of some 20 additional cancer fatalities among the estimated 200 million people who probably received radiation doses from Windscale [106,119], compared to the expected normal incidence of about 50 million cancer fatalities in a population of this size.

In the case of the Three Mile Island-2 accident, the best-estimate public collective dose of about 35 person-sieverts indicates that, assuming a Poisson distribution, there is about a 25% chance that there will be one excess cancer fatality and about a 70% chance that there will be no excess cancer fatalities.

TABLE 22
Reactor Accidents with Fuel Damage and/or Radioactive Releases

Reactor	Date	Thermal Power, MW	Fuel Damage	Radioactive Releases		Early Fatalities	Max. Indiv. Dose	Collective Dose (Person-Sv)	Notes
				In Containment or Building	In Atmosphere				
Research and Test Reactors									
NRX, Canada	1952	30	Some fuel melting	10,000 Ci in water		0	0.16 Sv, on-site 0 Sv, off-site	26, on-site 0, off-site	(a)
HTRE, USA	~1958	0.12	68% fuel partially melted		I: 34 Ci Total: ~400 Ci	0	0	0	(b)
NRU, CANADA	1958	200	Damaged fuel rod burned during removal			0	0.19 Sv, on-site 0 Sv, off-site	12, on-site 0, off-site	(c)
WTR, USA	~1959	60	Some fuel melting	10,000 Ci in water	I: 0 Ci Noble Gases: <800 Ci	0	0.02 Sv, on-site 0 Sv, off-site	0	(d)
ETR, USA	~1961	175	18 fuel plates partly melted	42 Ci in water	6.4 Ci	0			(e)
MTR, USA	1962	40	Part of one fuel plate melted	Low levels in air	None	0		0	(f)
ORR, USA	1963	24	Part of one fuel plate melted	1000 Ci in coolant	I: 0.15 to 0.20 Ci	0			(g)

NOTES

a) Heavy-water-moderated, light-water-cooled. No containment. Human error and mechanical design fault caused brief power surge to ~3 times full power. Partial melting of some U-metal fuel rods resulted. Reactor core replaced and reactor re-started in 1954, and is still in operation. References: 102, 103

b) Heat Transfer Reactor Experiment. Zirconium-hydride-moderated, once through air-cooled. No containment. Power excursion partially melted ~68% of fuel (UO_2 powder dispersed in 80 Ni-20Cr alloy). Reference: 102

c) Heavy-water-moderated, heavy-water-cooled. No containment. Ruptured aluminum clad U-metal fuel rod ignited after cooling lost when damaged rod stuck in flask during removal from core. Portions of fuel rod debris fell on top of reactor and in maintenance pit. References: 102, 104

d) Westinghouse Test Reactor. Containment. Some fuel element melting. Shut-down in 1962. References: 102, 105, 131

e) Engineering Test Reactor. U-metal plate-type fuel elements. Containment. Flow blockage resulted in partial melting of 18 fuel plates. Reference: 102, 131

f) Materials Test Reactor. U-metal plate-type fuel elements. Containment. Flow blockage resulted in melting of part of one fuel plate. Reference: 102

g) Oak Ridge Research Reactor. U-metal plate-type fuel elements. Containment. Flow blockage resulted in melting of the top section of one fuel plate. About 1000 Ci of fission products released to the coolant. About 0.15 to 0.20 Ci of iodine released to atmosphere through stack scrubber and filter. Reference: 102

TABLE 22 (cont'd)

Reactor Accidents with Fuel Damage and/or Radioactive Releases

Reactor	Date	Thermal Power, MW	Fuel Damage	Radioactive Releases		Early Fatalities	Max. Indiv. Dose	Collective Dose (Person-Sv)	Notes
				In Containment or Building	In Atmosphere				
PRTR, USA	1965	7	Defected fuel rod failed	I: 7Ci(0.9%)	0	0		0	(h)
Military Reactors									
Windscale-1, UK	1957	250	Fuel burned in graphite fire		I: 2×10^4 Ci (12%) Noble Gases: 3.4×10^5 Ci Others: 2300 Ci	0	0.045 Sv, on-site 20 mSv, off-site	$\sim 2 \times 10^3$	(i)
SL-1, USA	1960	3	Partial core melt		I: 80 Ci (<0.5%) Noble Gases: 10^4 Ci	2	0.27 Sv, on-site	~0	(j)
Power Reactors									
Enrico Fermi, USA	1966	300	Two assemblies partly melted	None	None	0	0	0	(k)
Lucens, Switzerland	1969	28	7 fuel channels overheated and distorted		I: 0.49 mCi Noble Gases: 92 Ci Other: neg.	0	~1.5 mSv, on-site ~0.05 mSv, off-site	0	(l)
Brown's Ferry 1 & 2, USA	1975	3293	None	None	None	0	0	0	(m)
Three Mile Island-2, USA	1979	2720	Large portion of core melted		I: 14 Ci Noble Gases: 10^7 Ci	0	0.042 Sv, on-site 0.70 mSv, off-site	~35	(n)

NOTES

h) Plutonium Recycle Test Reactor. Pressure tube reactor. Containment. Intentionally defected fuel rod failed and caused failure of a pressure tube, which released iodine from coolant water to containment. Reference: 102

i) Graphite-moderated, gas-cooled. No containment. Plutonium production reactor, not a power reactor. Improper Wigner energy release led to graphite fire and U-metal fuel combustion. References: 102, 106, 119

j) Light-water moderated and cooled, highly enriched. No containment. Military demonstration power reactor. Excess reactivity addition led to explosive expulsion of core water and partial core melting. Two operators killed by blast. Reference: 102

k) Fast breeder demonstration power reactor. Sodium cooled. Containment. Foreign object caused flow blockage to two fuel assemblies which partially melted. Reactor repaired and returned to service. Reference: 107

l) Gas-cooled, heavy-water-moderated, vertical-pressure-tube reactor. Containment. Overheating of fuel led to swelling and distortion of about 7 fuel channels. Reactor shut down permanently. Reference: 108

m) General Electric BWR. Containment. Fire started by construction worker in adjacent unit destroyed control system cables to units. Cooling of cores of both units maintained throughout incident. No core damage. Reference: 109

n) Babcock-Wilcox PWR. Containment. Sequence of events led to small LOCA through stuck-open relief valve, which led to major core melt-down. Severe economic losses. References: 102, 110, 111

TABLE 22 (end)

Reactor Accidents with Fuel Damage and/or Radioactive Releases

Reactor	Date	Thermal Power, MW	Fuel Damage	Radioactive Releases		Early Fatalities	Max. Indiv. Dose	Collective Dose (Person-Sv)	Notes
				In Containment or Building	In Atmosphere				
Power Reactors (cont'd)									
Prairie Island-1, USA	1979	1650	None		I: 37 GBq (1 Ci) Noble Gases: 30 Ci	0	0	0	(o)
Crystal River-3, USA	1980	2452	None	I: 2 Ci Noble Gases: 1000 Ci	None	0	0	0	(p)
H.B. Robinson, USA	1981	2200	None	Very Small	None	0	0	0	(q)
R.E. Ginna, USA	1982	1520	None		<25% of regulatory guidelines	0	~0	0	(r)
Pickering-2, Canada	1983	1775	None	Very Small	None	0	~0	0	(s)
Sequoya-2, USA	1984	3423	None	Very Small	None	0	2 mSv, on-site 0 , off-site	0.16, on-site 0, off-site	(t)
Chernobyl-4, USSR	1986	3200	Major core destruction		I: ~7.3 MCi Noble Gases: ~46 MCi Total: ~96 MCi	31	~16 Sv, on-site ~0.4 Sv, off-site	~2.9×10^5	(u)

NOTES

o) Westinghouse PWR. Containment. Foreign object caused steam generator tube rupture resulting in a small LOCA. No core damage. Damaged and adjacent tubes plugged and reactor re-started after a few days. Reference: 112

p) Babcock-Wilcox PWR. Containment. Instrument and control system malfunction resulted in small LOCA into containment. No core damage. Reactor restarted after normal refuelling shut-down. References: 102, 112

q) Westinghouse PWR. Containment. Pressure transient ruptured bellows in isolation valve and blew off drain-line cap, resulting in a small LOCA. No core damage. Reactor returned to service after three days. Reference: 113

r) Westinghouse PWR. Containment. Steam generator pressure tube rupture resulted in a small LOCA. No core damage. Estimated maximum doses from off-site release significantly less than regulatory guidelines. Insignificant public health effects. Reference: 114

s) Ontario Hydro CANDU. Containment. Pressure tube rupture led to small LOCA into containment. No core damage during accident; two fuel bundles damaged during channel de-fuelling. This unit and Pickering-1 being re-tubed and will return to service 1987. Reference: 115

t) Westinghouse PWR. Containment. Human error during maintenance with reactor at 30% power caused break in seal of in-core instrument thimble resulting in a small LOCA. No core damage. Very low doses to workers involved. No releases off-site. Reference: 116

u) Soviet RBMK Reactor. Graphite-moderated, boiling water cooled. No containment over reactor. Abnormal operation caused power excursion which resulted in graphite fire, major core destruction and chemical explosion which destroyed building. Two operators killed by blast and 29 fire and other emergency workers killed by acute radiation doses. No fatalities among public from acute radiation doses. Maximum reported radiation field in evacuated area ~7.2 to 10 mSv/hr. Reactor has been entombed. References: 117, 118

The Soviet report on the Chernobyl-4 accident [118] indicates that about 75 million people in the European part of the USSR may have been exposed to radiation from Chernobyl-4 and that the total collective dose commitment for the next 50 years to this population is 290,000 person-sieverts. Thus, using the usual risk coefficient, there is an estimated risk of about 2900 additional cancer deaths in this population, compared to the expected number of about 10 million [118]. That is, there is an estimated increase of about 0.03% in risk of cancer to an individual in this population. Any such increase would not be detectable statistically. The Chernobyl-4 accident also resulted in estimated collective doses outside the USSR, but these all appear to be quite small [120].

It should be noted that the two most severe reactor accidents, Windscale and Chernobyl, have occurred in graphite-moderated reactors, one of which was gas-cooled, the other boiling-water-cooled. Thus in both cases there was no significant mass of water in the core region. There is considerable experimental evidence to show that iodine and other volatile fission products, excluding noble gases, considering their chemical forms in the fuel and upon release from the fuel, are very soluble in water under the conditions encountered in reactor accident sequences (e.g. 102,121,122). Therefore, most of these fission products should be retained in the moderator and coolant in severe reactor accidents in water-cooled-and-moderated reactors. In addition, research has shown the importance of a high-moisture atmosphere in the reactor building following a severe accident in promoting such processes as aerosol formation, adsorption and deposition for removal of fission products from the atmosphere [102,123, 124]. Thus, we would expect that very little iodine, cesium and other fission products would be available in the reactor building atmosphere for ready release to the environment in a severe accident in a reactor with a large water inventory. This anticipated behaviour has been substantiated by the evidence of very low volatile fission product, other than noble gas, releases to containment or the environment in the accidents to water-cooled-and-moderated reactors in which fuel damage occurred, as shown in Table 22.

There is only one known case in which there may have been an accident with significant public impact in other parts of the nuclear fuel cycle. This case is an apparent accident associated with waste management at Kyshtym in the USSR [106,125]. However, there is virtually no reliable information available on this accident and the highly speculative possible causes advanced imply nuclear technologies and waste management procedures which have no relevance to commercial nuclear power in the western world [106].

7.3.2 **Hypothetical Catastrophes**

Probabilistic risk assessment (PRA) has, in applications to energy systems, been most often applied in estimating the risks of hypothetical catastrophic accidents in nuclear power plants. The initial major study, the Reactor Safety Study [100], was completed in the USA in 1975. Since then, a significant number of risk studies has been completed in a number of countries [126,127,128]. The importance and usefulness of such studies in identifying the component and system failures that are the major contributors to overall risk and in enabling cost-effective improvements to be made when required has been clearly recognized, particularly since the Three Mile Island-2 accident.

While the major usefulness of these studies from the point of view of public safety lies in the areas mentioned above, the hypothetical risks of catastrophic accidents in nuclear power plants estimated in these studies can be usefully presented, as mentioned earlier, in risk curves, as given in Figure 1, from the Rasmussen study [100]. Figure 1 gives the probability distributions for acute fatalities resulting from accidents to a typical PWR and a typical BWR in the USA. Similar curves were also produced for latent cancer fatalities, thyroid illnesses, genetic effects, property damage, and evacuation area. To provide perspective for such risk curves, Figure 2, also from the Rasmussen study, compares the risk curve for the total acute fatalities from accidents in 100 nuclear power plants in the USA to the risk curves for other man-caused accidents.

The methodology and data base for probabilistic risk analysis have improved considerably since the Rasmussen study was completed. Risk curves for acute fatalities from two more-recent PRA studies in the USA, for the Zion [129] and Indian Point [130] nuclear power plants are shown in Figure 3, where they are compared to the average curve from the Rasmussen study. Of course, in comparing complementary cumulative distribution function (CCDF) risk curves from different PRAs, it must be recognized that the scopes, assumptions and methodologies used may be different, so that care must be exercised in drawing conclusions from such comparisons. For example, differences may arise because of different depths of analysis of accident sequences, the use of different failue rate data bases, the treatment of external events such as earthquakes, fires and floods and the treatment of common cause events and of human actions (e.g., errors or post-accident recovery actions). It is also important that the treatment of uncertainties is comparable and that, for example, median risk curves are not compared to mean-value risk curves. Of course, the population density and distribution around a given nuclear power plant will also affect the results. In this respect, the risk curves for the Zion and Indian Point 3 plants in Fig. 3 are of interest since these plants are in close proximity to the cities of Chicago and New York, respectively.

While risk curves, as shown in Figures 1 to 3, are the most informative means of presenting risks for large hypothetical accidents, the expected value of the total risk can also be determined, by appropriate integration of the risk curves. For example, the expected value of the total risk of acute and latent fatalities from accidents to the typical reactors analyzed in the Rasmussen study expressed in the terms used in this report, fatalities per GWa, can be estimated from reference 100, by assuming an average capacity factor of 75% for the reactors. The resulting risk is estimated to be about 0.03 public fatalities per GWa, well below the ranges of total public risk for normal operation of the nuclear fuel cycle given by Paskievici (0.1 to 0.42) and by Niehaus (0.27 to 0.33) as shown in Table 12.

7.3.3 Assessment for Canada

There have been no power reactor accidents in Canada leading to any significant occupational exposures, including the most serious, listed in Table 22, the pressure tube rupture in the Pickering-2 reactor in August, 1983. As indicated there, this in-core LOCA resulted in no injuries or significant occupational over-exposures or in any releases of radioactivity outside containment [115].

No probabilistic risk analysis has yet been completed for a CANDU reactor, but such a study is now being undertaken by Ontario Hydro for the Darlington reactor [132]. However, it is unlikely that the risks of hypothetical catastrophic accidents in a CANDU would be greater than those in a PWR or BWR, considering the conservative approaches to reactor safety used in Canada [133] and taking into account certain mitigating factors in the CANDU design. Studies of severe accident conditions in CANDU reactors show that, unlike the case for LWR's, there will be no gross fuel melt-down even for a large LOCA combined with loss of emergency coolant injection (LOECI) during the accident sequence, because of heat transfer to the moderator with its separate and independent cooling system [134-137]. Furthermore, a study [138,139] has shown that, should the moderator heat sink be lost following a large LOCA plus LOECI in a CANDU, while gross core melting would eventually occur in this case, the calandria, separately cooled by the shield tank cooling system, would serve as an effective core-catcher, preventing base mat melt-through of the core. Also, there would probably be no consequent failure of containment above ground in such an accident sequence.

With two independent and diverse safety shutdown systems, the probability of gross core melt-down from reactor transients would be expected to be no higher in a CANDU reactor than in an LWR.

From the foregoing arguments, the probability and consequences (i.e., the risks) of core meltdown would be expected to be less for a CANDU reactor than for a PWR or BWR. Since the various PRA studies referred to earlier show that there is no significant danger for the public unless gross core meltdown occurs, it can be concluded that the risk associated with hypothetical low-probability, high-consequence accidents for a CANDU reactor in Canada is less than that estimated for LWR's in the USA.

As discussed in section 5.3.7, hydrogen sulfide used in the heavy water production process in Canada is a very toxic material. Therefore, the risk of public and occupational fatalities resulting from a catastrophic accident releasing H_2S at a heavy water production plant must be considered here.

Monserco, Ltd., [140] and Paskievici and Zikovsky [141] have made assessments of this risk. The Monserco study developed a methodology for the prediction of the conditional probabilities of public fatalities for a series of postulated accident sequences in a heavy water production plant using the GS process, specifically the Bruce heavy water plant [142]. However, the probabilities of the various hypothetical accidents are not estimated, so that the actual risks of the accident sequences and the overall risk of fatalities from accidents at a heavy water production plant are not given. Therefore, the results of the Monserco study cannot be used for the present purposes. Paskievici and Zikovsky [141] use various approaches to estimate the risks of human fatalities from the operation of GS-process, heavy water production plants. We can adapt and utilize these methods here.

First, an upper limit estimate of the risks of a catastrophic accident in a GS-process heavy-water production plant can be made based on the fact that no public nor occupational fatalities have occurred in the operation of such plants in North America. The upper-limit estimate of normalized risk from such accidents will be the same as that estimated for normal operation in section 5.3.7, i.e., about 10^{-3} fatalities/GWa.

Paskievici and Zikovsky [141] also estimate the fatality risk from a heavy water production plant based on the actual fatality records of catastrophic accidents from 1958 to 1980 of other chemical process plants which handle or process H_2S. From the 27 public and 24 occupational fatalities that have actually occurred in such plants, which handle an average of about 6.6×10^6 Mg of H_2S per year [141], assuming that these fatality rates apply to GS-process heavy water production plants, and an inventory of H_2S of 1.5 Mg/Mg of annual heavy water capacity, it can be estimated that the risk of public fatalities is about 9.4×10^{-6}/GWa and that of occupational fatalities is about 8.3×10^{-6}/GWa.

Paskievici and Zikovsky [141] also estimate the risks of public fatalities from H_2S exposures from certain severe hypothetical accident scenarios in GS-process, heavy-water production plants and in the transportation of H_2S to such plants and obtain values ranging from about 1.6×10^{-6} to about 4.3×10^{-5} fatalities/GWa.

In summary, based on experience with GS-process, heavy-water production plants and other chemical process plants handling H_2S, the public and occupational risks from catastrophic accidents are estimated to range from about 17.7×10^{-6}/GWa to an upper limit of about 10^{-3}/GWa, while the risks based on the analysis of hypothetical severe accident scenarios lie in the range of about 1.6×10^{-6} to 4.3×10^{-5} fatalities/GWa.

It is evident that all of these estimated risk figures, including the upper-limit experience value, are negligible compared to the risks of normal operation of nuclear power plants (See Tables 9,12,15,16) and to the total estimated risks of hypothetical severe accident sequences in nuclear power plants themselves (See section 7.3.2). Therefore, we can ignore these risks in our evaluation of the total risks of catastrophic accidents in the CANDU nuclear fuel cycle.

7.4 Catastrophes in the Hydro-Electric System

7.4.1 Serious Accidents That Have Occurred

The most obvious catastrophic accidents associated with hydro-electric power generation are dam accidents resulting in severe flooding and many deaths among the public. The International Commission on Large Dams (ICOLD) defines various types of dam failures or accidents [147]. Catastrophic accidents would be classified as ICOLD failures Types 1 and 2. Table 23 lists some of the major dam accidents that have occurred in this century [3, 5, 153]. It should be noted that some of these dams were used for purposes other than hydro-electric power generation. Table 23 shows that many of these dam accidents resulted in hundreds or even thousands of public fatalities.

Recently, in the industrialized countries, better engineering and construction techniques and effective inspection and monitoring procedures should have significantly reduced the risks of catastrophic dam accidents and the risk of public fatalities from those prevailing earlier [96, 148, 149].

Catastrophic accidents during construction of large dams can cause large numbers of occupational fatalities. We have found little information on such accidents [148].

Table 23

Some Catastrophic Dam Accidents*

Location	Year	Fatalities	Notes
Gleno, Italy	1923	600	
Coedty, Wales	1926	20-60	
St. Francis, Calif. USA	1928	450	(a)
Sella Zerbino, Italy	1935	100-111	
Vega de Tera, Spain	1959	123-150	(a)
Frejus (Malpasset), France	1959	421	Ref. 5
Oros, Brazil	1960	30-1000	
Babi Yar, USSR	1961	145	
Vaiont, Italy	1963	2600-3000	(b)
Koyna, India	1967	180	
Sempor, Indonesia	1967	200	(c)
Frias, Argentina	1970	>40	(c)
Buffalo Creek, U.S.A.	1972	125	(c)
Morvi, India	1979	1335	(d)
Stava, Italy	1985	270	(e)

* Some of these dams were used for purposes other than hydro-electric generation.

(a) Structural failure.
(b) Dam did not fail but flood occurred, caused by landslide into lake above dam.
(c) Failed by overtopping.
(d) Some estimates put the fatalities much higher.
(e) Piping failure.

7.4.2 Hypothetical Catastrophes

PRA studies have been undertaken to estimate the public risks from catastrophic failures of dams in California [143]. Estimated public fatalities from failures of concrete dams ranged from 34,000 up to as high as 260,000. It is generally accepted that the frequency of a concrete dam disaster is of the order of magnitude of 10^{-4} per dam-year [100, 144], although data show that recently constructed dams have a failure frequency significantly less than this value [148]. Nevertheless, applying the frequency value to these California dams results in estimated public risks ranging from 3 to 26 fatalities per year. These risks cannot readily be compared to those estimated for hypothetical catastrophic risks from nuclear power plants since many of these dams are not used for power production, so that the risk per GWa cannot be calculated.

7.4.3 Assessment for Canada

We are not aware of any catastrophic failures of hydro-electric (or other) dams in Canada. Of course, the possibility of such failures cannot be ruled out completely.

While some of the large hydro-electric dams are in the more populated parts of the country, a large number of existing dams are, and most of any future dams will be, located in remote areas where the population at risk from a dam failure is very low. Most of the high-head dams in Canada, which could be expected to cause the most fatalities from dam failures, are also located in remote areas.

No analyses of hypothetical catastrophic failures of hydro-electric dams corresponding to PRA's for nuclear reactors have been made in Canada.

8. CONCLUSIONS

8.1 Risks from Normal Operation

The total risks of occupational fatalities, from both diseases and accidents, for normal operation of the coal, nuclear and hydraulic energy systems are compared in Figure 4, where the best-estimate ranges of Niehaus and of Paskievici are shown for coal and nuclear and the ranges estimated by Holdren and by Inhaber, revised as discussed in the report, are shown for hydro-electricity. For the three energy systems, the tentative values estimated in this report for Canadian conditions are also shown in Figure 4.

Similarly, the total risks of public fatalities, from both diseases and accidents, for the three energy systems are compared in Figure 5.

As stated earlier, we will base our conclusions on the risks of normal operations for the coal and nuclear fuel cycles on the results of Niehaus and of Paskievici, with the tentative values estimated for Canada being noted. For the hydro-electric system, we will base our conclusions for occupational risk of normal operation mainly on the estimates which we have developed here because of the large difference between the estimates of Holdren and of Inhaber. Conclusions on the public risk from normal operation of the hydraulic generating system will be based on our results and those of Holdren.

Figure 4 shows that the occupational risks in the coal fuel cycle are about two to four times higher than the occupational risks in the nuclear fuel cycle, which are in turn about the same as those for hydro-electric generation. The major reasons for the higher occupational risks in the coal fuel cycle are the relatively high risks of coal mining and coal transportation, as shown in Table 2.

The estimates of occupational risks associated with the coal fuel cycle in Canada are seen in Figure 4 to be somewhat higher than those estimated by Niehaus and to be at about the middle of the range of those estimated by Paskievici. For the nuclear fuel cycle, Figure 4 shows that the estimates of occupational risks in Canada are below those estimated by Niehaus and by Paskievici. For hydraulic generation, Figure 4 shows that the estimate of the range of risks of occupational fatalities in Canada is somewhat higher than the range estimated by Holdren.

Figure 5 shows that the risks to the public from normal operation of the coal fuel cycle may be roughly an order of magnitude greater than those from the nuclear fuel cycle, which are in turn somewhat greater than those from hydraulic generation. However, it must be recognized, as discussed earlier, that there is considerable uncertainty in the health effects of air pollution caused by coal-

burning, which is the major contributor to the high public risks from the coal fuel cycle.

Figure 5 also shows that the estimates of public risks from normal operation of the coal fuel cycle in Canada are within the ranges estimated by Paskievici and by Niehaus. However, the estimates for Canada exclude long-distance effects of air pollution. Figure 5 also shows that the estimates of public risks from normal operation of the nuclear fuel cycle in Canada are less than those estimated by Paskievici and by Niehaus, and that the tentative range of estimates of public risks from normal operation of hydraulic generation in Canada is about an order of magnitude less than the range estimated by Holdren.

Of course, in considering these comparisons and conclusions, the assumptions and qualifications in the various estimates, as discussed earlier, must be kept in mind.

The major uncertainty in these estimates appears to be in public risks from coal combustion. If, as some investigators believe, there are no adverse health effects of low concentrations of sulfates and other pollutants, then the coal fuel cycle total public risk estimate range would be reduced significantly, to about 0.58 to 1.44 fatalities/GWa, from the results of Niehaus. However, this range would still be greater than the ranges of public risks from the nuclear fuel cycle and from hydraulic generation, as can be seen from Figure 5.

8.2 Risks from Catastophic Accidents

Catastrophic accidents have occurred in each of the energy systems studied. However, the infrequent occurrence of such accidents precludes any quantitative estimates of the risks of such accidents based on experience. On the other hand, each of these catastrophes has provided new insights and improvements in design, construction and operation with the result that recently-built systems, undoubtedly, are less susceptible to catastrophic behavior than were earlier ones.

While probabilistic risk analyses of hypothetical catastrophic accident sequences can produce quantitative estimates of the risks of public and occupational fatalities in these energy systems, meaningful quantitative comparisons are not yet possible partly because the other systems have not been analyzed to the same extent as nuclear energy systems. In addition, even for nuclear energy systems, there are residual uncertainties in the methodology and input data.

Catastrophic accidents associated with the energy systems considered here have not occurred in Canada, nor have any PRA studies of catastrophic accidents yet been completed for Canadian conditions. Nevertheless, for various reasons given in the report, we would expect the risks of catastrophic accidents in all of these systems in Canada to be lower than those estimated for similar systems elsewhere. In particular, as discussed in section 7.3.3, in our judgment the risks of public and occupational fatalities from catastrophic accidents in the CANDU reactor system or in its fuel cycle are lower than those of the light water reactor systems and their fuel cycles.

Finally, on the information provided here, there is no evidence that the risks of occupational and public fatalities from catastrophic accidents are significantly different among the Canadian energy systems studied here.

8.3 Overall Conclusions

As this report has amply indicated, it is difficult to make an unequivocal comparison of the risks of occupational and public fatalities amongst the different electrical energy systems studied here. However, for normal operation, the data indicate that occupational risks in the coal fuel cycle are significantly higher (2 to 4 times) than those in the nuclear and hydraulic systems. Also the results suggest, pending further epidemiological investigations, that coal-fired (and oil-fired) systems present greater risks to the public than do nuclear and hydraulic systems.

The absence of catastrophic accidents plus the existence of certain special conditions in Canada suggest that the risks of public and occupational fatalities from such events are very low for all the technologies assessed in this report, and furthermore are lower here than in the world at large. In particular, in our judgment, the risks of fatalities from catastrophic accidents in CANDU reactor systems are lower than those in the PWR and BWR systems.

However, the complex decision to use a specific technology will take into account many other socio-economic factors as well as the risks of public and occupational fatalities. Such factors include capital and operating costs of the technology, reliability of electricity supply, environmental impacts, considerations of industrial infrastructure, opportunities for employment, considerations of foregone land use not only for normal operation but also following catastrophic accidents and genetic and non-fatal health effects. Political considerations will also be an important factor.

To conclude, we believe that this report provides a reasonable assessment of the risks of occupational and public fatalities from electrical generation by the large-scale energy systems that are technically and economically viable for the next quarter-century in Canada. This assessment places the risks of nuclear generation of electricity into perspective with those of the feasible alternatives for the near future. The results also help to assure the Advisory Committee on Nuclear Safety that the first qualitative safety goal proposed in its report "Safety Objectives for Nuclear Activities in Canada" [145] that "Nuclear activities should not lead to unacceptable risks to the workers involved or to the general public" is being achieved.

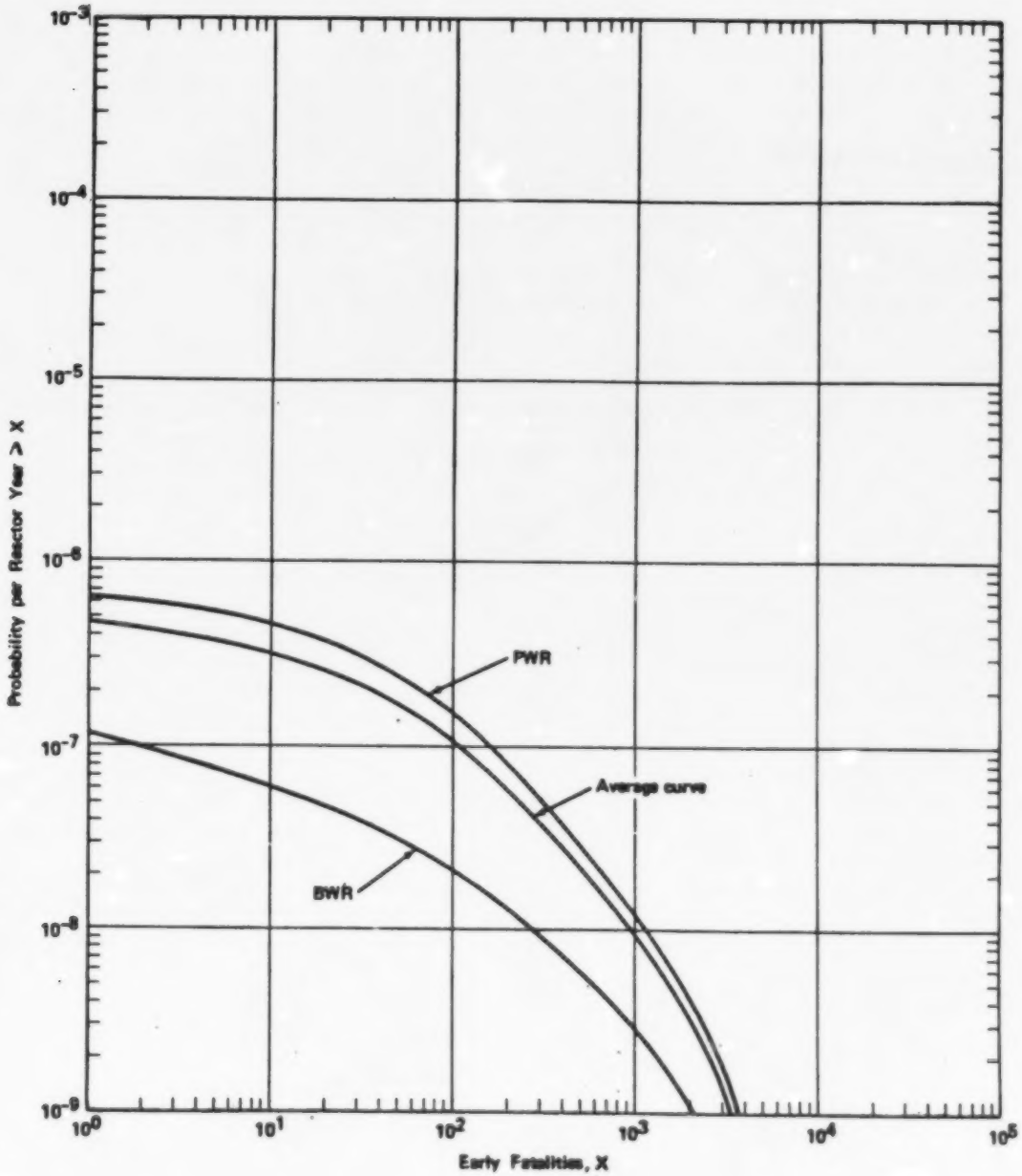


Figure 1:Probability distribution for early fatalities per reactor year (WASH-1400)

Note: Approximate uncertainties are estimated to be represented by factors of 1/4 and 4 on consequence magnitudes and by factors of 1/5 and 5 on probabilities.

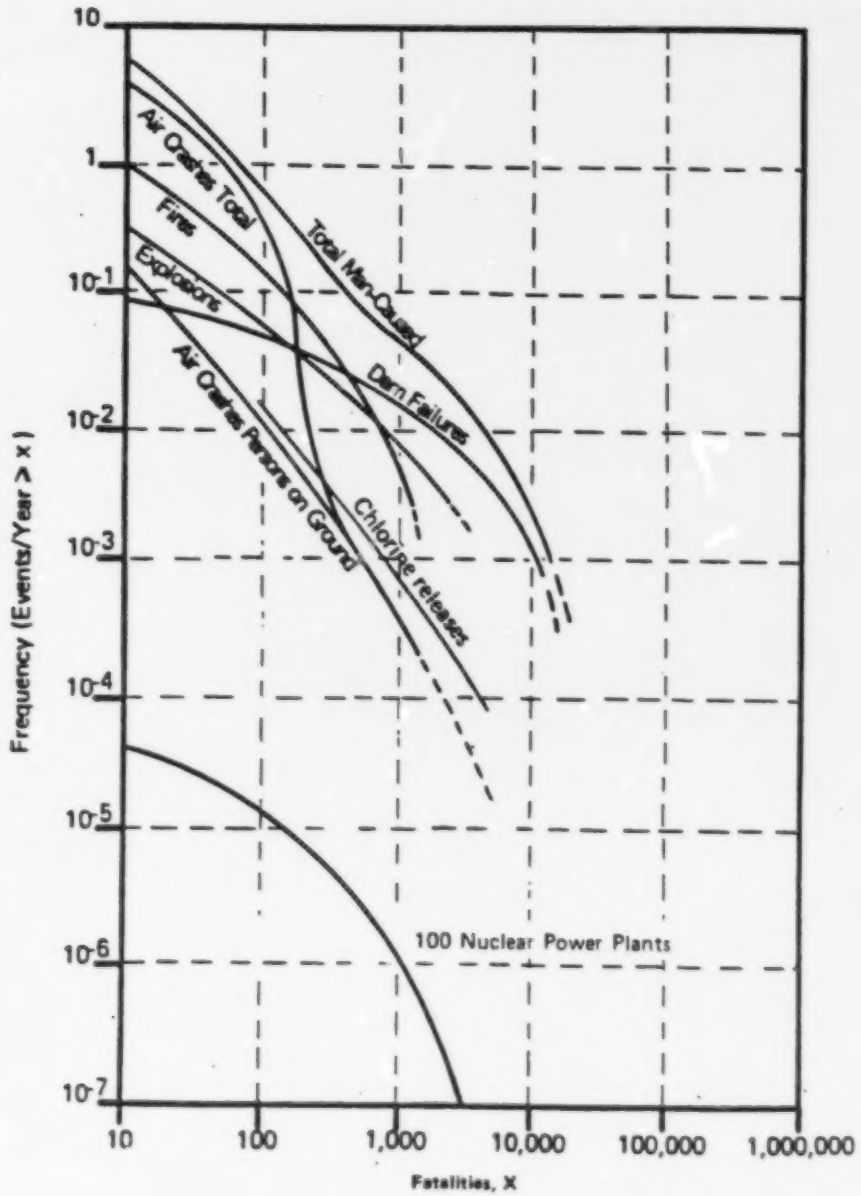
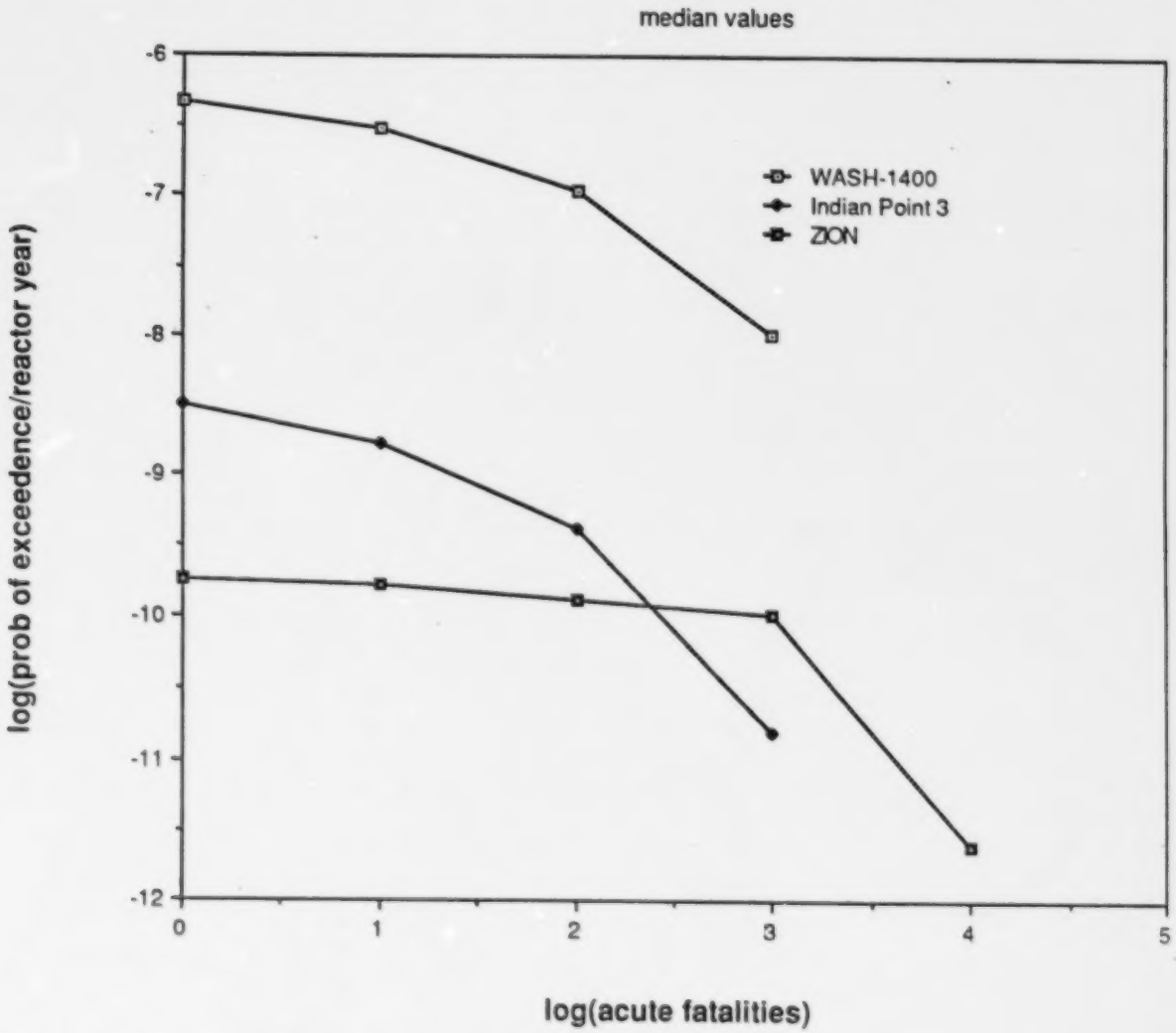


Figure 2: Frequency of man-caused events involving fatalities (WASH-1400)

FIGURE 3: Probability distributions for early fatalities



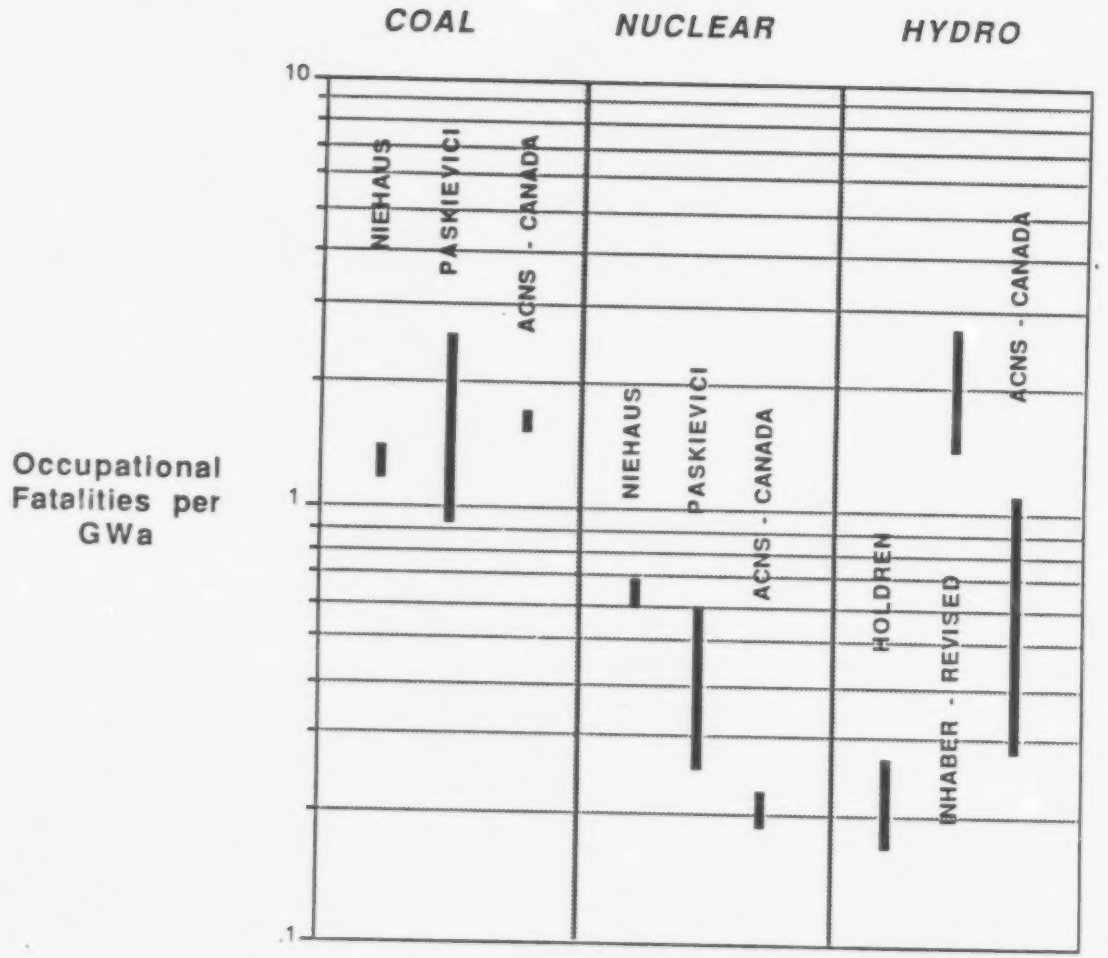


FIG. 4: Risks of occupational fatalities from electrical energy systems

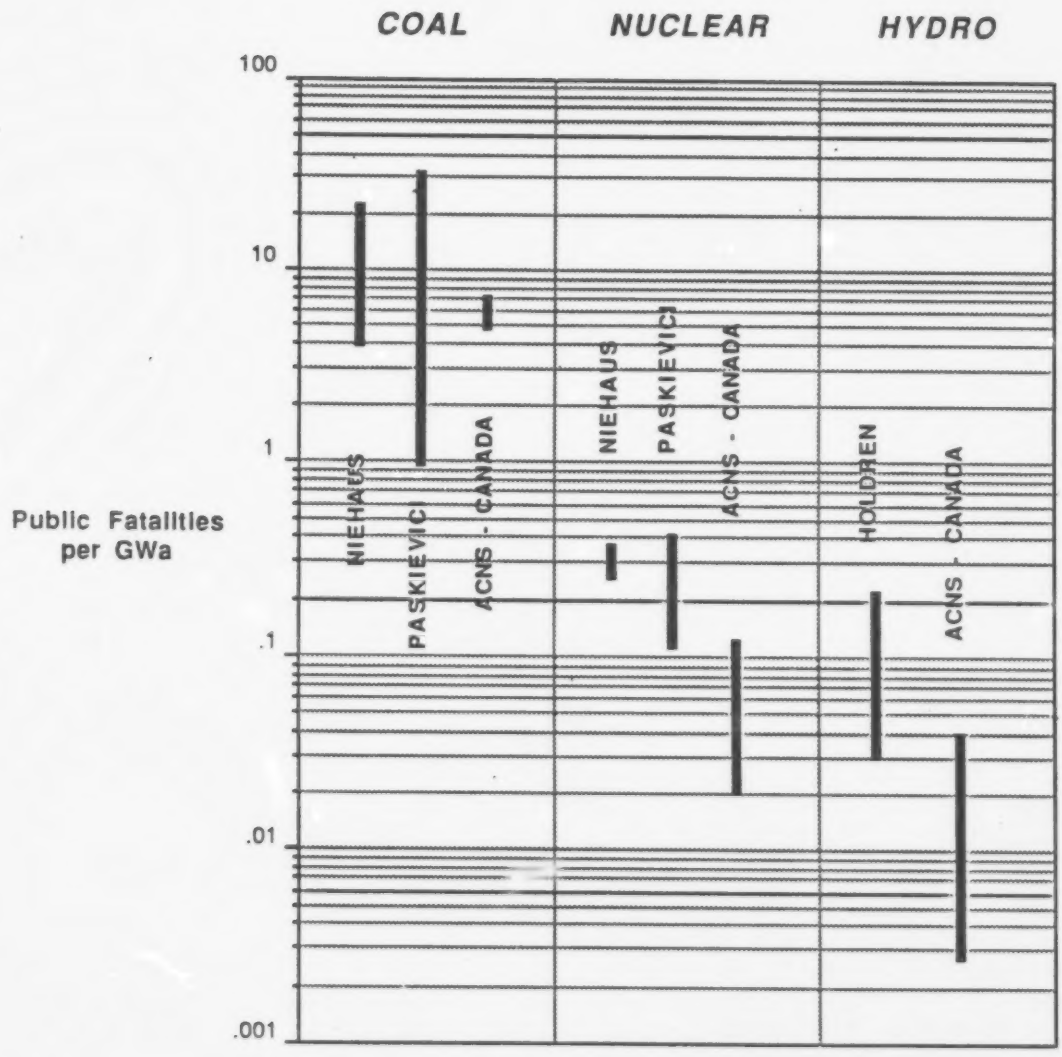


FIG. 5: Risks of public fatalities from electrical energy systems

APPENDIX 1

RISKS OF FATALITIES FROM THE OIL FUEL CYCLE

As promised in section 1 of this report, we provide in this Appendix a brief summary of the occupational and public risks from the fuel cycle for oil-fired electrical generation plants. We again take the best-estimate results of Paskievici [6,8,9,10,12] and of Niehaus [7,11,13] as the most credible estimates of the risks for this fuel cycle. The methodology and assumptions used by Paskievici and by Niehaus in arriving at these best-estimate values are the same as those which have been described in the main body of this report for the other fuel cycles.

The ranges of occupational fatalities associated with electricity production from oil-fired power plants are given in Table 1-1 and the ranges of public fatalities are given in Table 1-2.

Table 1-1 shows that the total occupational fatalities for the oil fuel cycle are about the same as those for the nuclear-fuel cycle and for hydraulic generation and are considerably less than those for the coal fuel cycle [see Figure 4). Table 1-2 shows that the total public fatalities for the oil fuel cycle are comparable to the high estimated values for the coal fuel cycle, again because of air pollution from combustion, and are thus an order of magnitude higher than the estimated total public fatalities from the nuclear fuel cycle and from hydraulic generation (see Figure 5).

As for the coal and nuclear fuel cycles, the best estimates of Paskievici and Niehaus for the oil fuel cycle, as given in Tables 1-1 and 1-2 ignore risks from catastrophic accidents. Catastrophic accidents can occur in the oil fuel cycle, such as large refinery fires and explosions [5,146], which can result in thousands of predicted fatalities in the public, albeit with very low probabilities.

Table 1-1

Occupational Fatalities in the Oil Fuel Cycle

(Fatalities/GWa)

Sources	Cause of Fatality	Range
Paskievici	Diseases	~0
	Accidents	0.23 - 0.53
Niehaus	Diseases	-
	Accidents	0.52

Table 1-2

Public Fatalities in the Oil Fuel Cycle

(Fatalities/GWa)

Sources	Cause of Fatality	Range
Paskievici	Diseases	0.3 - 30
	Accidents	~0
Niehaus	Diseases	1.1 - 7.5
	Accidents	0.0008 - 0.0019

APPENDIX 2

RISKS OF FATALITIES FROM THE GAS FUEL CYCLE

As in Appendix 1, we again take the best-estimate results of Paskievici [6,8,9, 10,12] and of Niehaus [7,11,13] as the most credible estimates of occupational and public risks from the gas fuel cycle. Again, note that the methodology and assumptions used by Paskievici and by Niehaus in arriving at these values have been described in the main body of this report.

The ranges of occupational fatalities associated with electricity production from gas-fired power plants are given in Table 2-1 and the ranges of public fatalities are given in Table 2-2.

Table 2-1 shows that the total occupational fatalities for the gas fuel cycle are slightly less than those for the nuclear fuel cycle and for hydraulic generation and thus are considerably less than those for the coal fuel cycle (see Figure 4). Table 2-2 shows that the total public fatalities for the gas fuel cycle, according to Paskievici, are towards the low end of the estimates for hydraulic generation, but are comparable, according to Niehaus, to those for nuclear power and above those for hydraulic generation (see Figure 5).

Although catastrophic accidents in the gas fuel cycle are seldom analyzed, major gas explosions are conceivable, and the possible use of LNG or LPG presents the possibility of catastrophic vapor explosions. As with the oil fuel cycle the probability of such events should be quite low.

Table 2-1

Occupational Fatalities in the Gas Fuel Cycle

(Fatalities/GWa)

Sources	Cause of Fatality	Range
Paskievici	Diseases	~0
	Accidents	0.13 - 0.30
Niehaus	Diseases	~0
	Accidents	0.30

Table 2-2

Public Fatalities in the Gas Fuel Cycle

(Fatalities/GWa)

Sources	Cause of Fatality	Range
Paskievici	Diseases	~0
	Accidents	0.006 - 0.014
Niehaus	Diseases	0.005 - 0.036
	Accidents	0.35

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